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HIGH POWER MFT DESIGN OPTIMIZATION

Drazen Dujic & Marko Mogorovic
École Polytechnique Fédérale de Lausanne
Power Electronics Laboratory
Switzerland

EPFL

pel

INSTRUCTORS

Drazen Dujic

Experience:

2014 – today	École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland
2013 – 2014	ABB Medium Voltage Drives, Turgi, Switzerland
2009 – 2013	ABB Corporate Research, Baden-Dättwil, Switzerland
2006 – 2009	Liverpoool John Moores University, Liverpool, United Kingdom
2003 – 2006	University of Novi Sad, Novi Sad, Serbia

Education:

2008	PhD, Liverpoool John Moores University, Liverpool, United Kingdom
2005	M.Sc., University of Novi Sad, Novi Sad, Serbia
2002	Dipl. Ing., University of Novi Sad, Novi Sad, Serbia

Marko Mogorovic

Education:

Pending	PhD, École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland
2015	M.Sc., École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland
2013	Dipl. Ing., University of Belgrade, Belgrade, Serbia

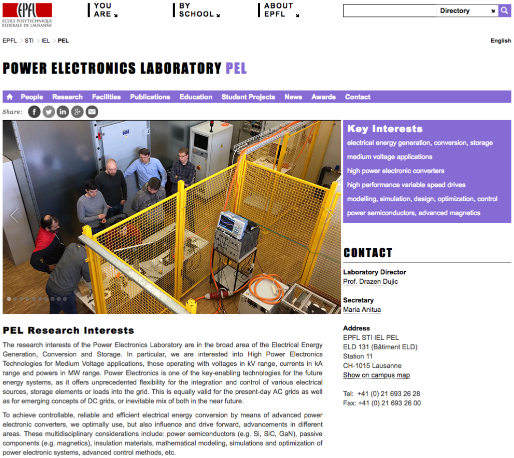
POWER ELECTRONICS LABORATORY AT EPFL

École Polytechnique Fédérale de Lausanne

School of Engineering

EPFL — STI — IEL — PEL

Institute of Electrical Engineering



- Online since February 2014
- `http://pel.epfl.ch`

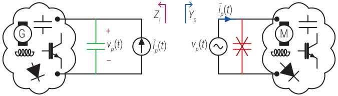
Competence Centre

RESEARCH FOCUS

MVDC Technologies and Systems

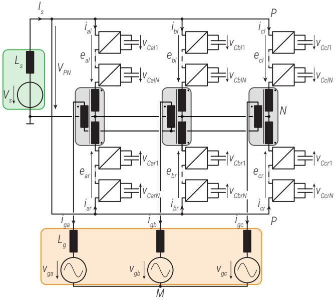
- System Stability
- Protection Coordination
- Power Electronic Converters

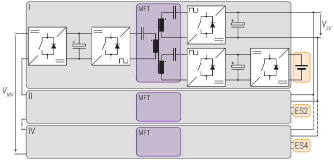
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



High Power Electronics

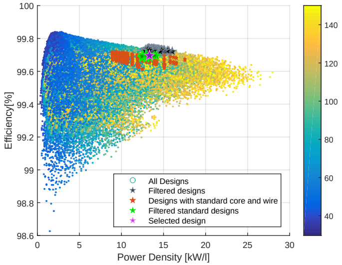
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

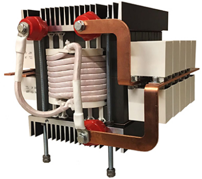




Components

- Semiconductor devices
- Magnetics
- Characterization





SCHEDULE

Before the Coffee Break

1) Introduction and Motivation
- Solid State Transformers
- Railway and Utility SST
- Medium Frequency Conversion

2) Medium Frequency Transformers
- Scaling laws
- Requirements
- Challenges

3) MFT Design Examples
- Railway related designs
- Utility related designs
- Other state-of-the-art designs

After the Coffee Break

4) Materials
- Magnetic materials
- Winding materials
- Dielectric materials

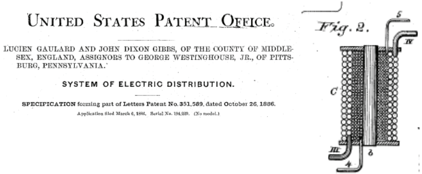
5) MFT Modeling
- Core
- Winding
- Thermal

6) MFT Design Optimization
- Optimization based algorithms
- Brute force parametric optimization
- Design examples

INTRODUCTION and MOTIVATION

Why high power medium frequency transformers are important technology?

IEC 60076-1 definition - Power Transformer: *A static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.*



United States Patent Office.

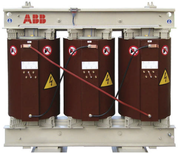
LUCIEN GAULARD AND JOHN DIXON GIBBS, OF THE COUNTY OF MIDDLESEX, ENGLAND, ASSIGNORS TO GEORGE WESTINGHOUSE, JR., OF PITTSBURG, PENNSYLVANIA.

SYSTEM OF ELECTRIC DISTRIBUTION.

SPECIFICATION forming part of Letters Patent No. 351,589, dated October 26, 1886.

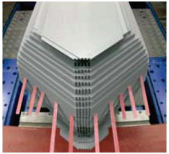
Line Frequency Transformers

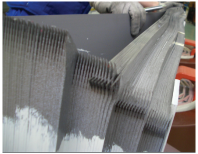
- Around for more than 100 of years
- Operated at low (grid) frequencies: 16.7Hz, 25Hz, 50/60Hz
- Standardized shapes and materials
- Cheap: ≈ 10kUSD / MW
- Efficient: above 99 % for utility applications
- Simple and reliable device



What are the problems?

- Bulky - for certain applications
- Inefficient - for certain applications
- Uncontrollable power flow
- Fixed transformation (power, voltage, current, frequency)





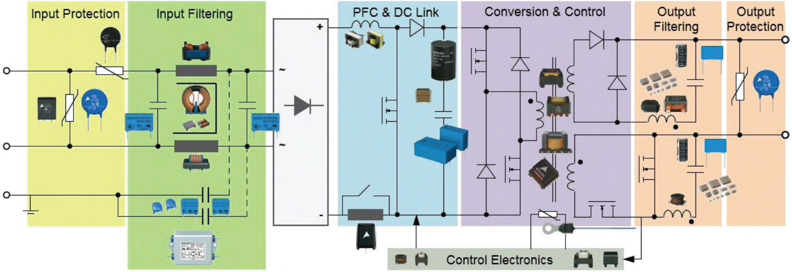
▲ Source: www.abb.com

MEDIUM-HIGH FREQUENCY CONVERSION

Switched Mode Power Supply (SMPS) Technologies

- Medium or High frequency conversion is not a new thing!
- Widely deployed in low voltage/power applications
- High efficiency
- Galvanic isolation at high frequency (standardized core sizes and shapes)
- Compact size (e.g. laptop chargers)
- Increased power density
- Cost savings

Could a Solid State Transformer provide that for a High Power Medium Voltage Applications?



▲ SMPS Technologies; Source: www.mouser.ch/new/tdk/epcos-smps/

SOLID STATE TRANSFORMERS

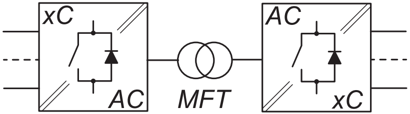
What is a Solid State Transformers?

- Not a transformer replacement?
- Should not be compared against 50/60 Hz transformer!

What is it?

- A converter
- A converter with galvanic isolation
- Can be designed for DC and AC (1-ph, 3-ph) grid
- Can be used in LV, MV and HV applications
- Can be made for AC-AC, DC-DC, AC-DC, DC-AC conversion
- Has power electronics on each terminal
- Transformer frequency higher than 50/60 Hz

Excellent tutorials are available at: https://www.pes.ee.ethz.ch



▲ Simplified SST concept

J. W. Kolar, J. Huber	Fundamentals and Application-Oriented Evaluation of Solid-State Transformer Concepts	Tutorial at the Southern Power Electronics Conference (SPEC 2016), Auckland, New Zealand, December 5-8, 2016
J. W. Kolar, J. E. Huber	Solid-State Transformers - Key Design Challenges, Applicability, and Future Concepts	Tutorial at the Internal Conference on Power Electronics and Motion Control (PEMC 2016), Varna, Bulgaria, September 25-30, 2016
J. W. Kolar, J. Huber	Solid-State Transformers - Key Design Challenges, Applicability, and Future Concepts	Tutorial at the 8th International Power Electronics and Motion Control Conference (IPEMC 2016-ECCE Asia), Hefei, China, May 22-25, 2016
J. W. Kolar, J. Huber	Solid-State Transformers: Key Design Challenges, Applicability, and Future Concepts	Tutorial at the Applied Power Electronics Conference (APEC), Long Beach, CA, USA, Mar. 20-24, 2016
R. Burkart, J. W. Kolar	Advanced Modeling and Multi-Objective Optimization / Evaluation of SiC Converter Systems,	Tutorial at the 3rd IEEE Workshop on Wide Bandgap Power Devices and Applications (WiPDA 2015), Blacksburg, USA, Nov. 2-5, 2015
R. Bosshard, J. W. Kolar	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the the 17th European Conference on Power Electronics and Applications (ECCE Europe 2015), Geneva, Switzerland, September 8-10, 2015
R. Bosshard, J. W. Kolar	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the 9th International Conference on Power Electronics (ICPE 2015-ECCE Asia), Seoul, Korea, June 1-5, 2015
R. Bosshard, J. W. Kolar	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the Conference for Power Conversion and Intelligent Motion (PCIM Europe 2015), Nuremberg, Germany, May 19-21, 2015
J. W. Kolar, J. Huber	Solid-State Transformers in Future Traction and Smart Grids	Tutorial at the Conference for Power Conversion and Intelligent Motion (PCIM Europe 2015), Nuremberg, Germany, May 19-21, 2015
G. Ortiz, J. W. Kolar	Solid State Transformer Concepts in Traction and Smart Grid Applications	Seminar at the Conference for Power Electronics, Intelligent Motion, Power Quality (PCIM South America 2014), São Paulo, Brazil, October 14-15, 2014.

APPLICATIONS

Railway

- 1-phase AC grids [1]
- Few voltage levels: 15kV (16.7Hz) or 25kV (50Hz)
- Low frequency (historically): (15kV) 16.7Hz or (25kV) 50Hz
- On-board installations - serious space constraints
- Volume and Weight reduction - system savings
- Reliability - high number of devices?
- Efficiency - easy to beat traction LFT
- Control - similar to existing solutions
- Cost?

▲ ABB's PETT (Source: www.abb.com)

Utility

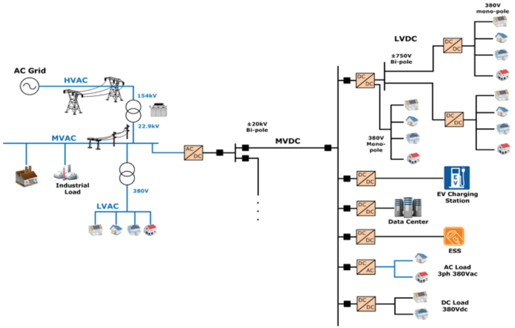
- 3-phase AC grids
- Many voltage levels: 3.3, 4.16, 6, 11, 15, 20kV, ...
- Grid frequency: 50Hz or 60Hz
- Sub-station installations - relatively low space constraints
- Volume and Weight reduction - not that relevant
- Reliability - even more complex due to 3-phases
- Efficiency - hard to beat distribution LFT
- Control - improved compared to existing solutions
- Cost?

▲ GE's SST [2] (Source: www.ge.com)

APPLICATIONS (CONT.)

MVDC Grids

- Increased interest into DC grids
- Need for high power DC-DC converters
- Galvanic isolation seen as necessary
- Bidirectional power flow
- High efficiency



▲ MVDC grids (Source: www.english.hhi.co.kr)

Marine LVDC / MVDC Distribution

- System level benefits
- Improved partial load efficiency
- No frequency synchronization of generators
- Integration of storage technologies
- Protection coordination

▲ MVDC marine distribution (Source: www.abb.com)

RAILWAY ON-BOARD ELECTRICAL SYSTEM

Railway on-board transformers:

- Step-down voltage to low levels
- Already optimized for low weight and volume
- Reduced efficiency as a price to pay
- Form factor depends on the mounting method
- Predominantly oil cooled / insulated
- Air cooled / solid insulation available as well

Few things to consider:

- 50Hz transformer is already fairly small
- 16.7Hz transformer is relatively bulky and inefficient
- Single galvanic isolation - insulation coordination
- Often, new train design defines the available space
- Design customization is common
- Power levels are modest and below 15MW
- Different from the utility transformers

▲ Various realization of traction transformers, Source: www.abb.com

RAILWAY SST

What traction SST offers in perspective:

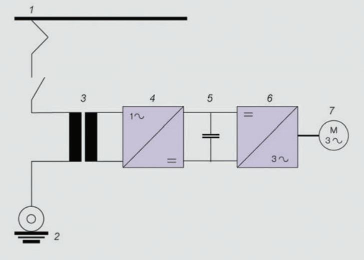
- Improved efficiency (specially for 15kV, 16.7Hz systems)
- Weight reduction - less raw materials
- Volume reduction - questionable due to insulation coordination
- Control features

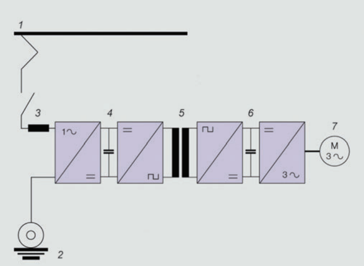
Why is traction SST not out yet?

- Conservative traction market
- Lack of business case
- Reliability concerns
- Very hard to compete in 25kV, 50Hz grids
- Not a major performance increase
- Increased cost compared to state-of-the-art solutions

Prototypes

- ALSTOM
- ABB
- BOMBARDIER
- ...





▲ On-board traction system evolution with SST [1]

ALSTOM - 1.5MW E-TRANSFORMER

Ratings

- Power: 1.5MW
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1650 V
- Weight: 3.1 t (vs 6.8 t 16.7Hz LFT)
- Volume: 3.22 m^3
- Efficiency: 94%
- Cost: 50% increase

Topology

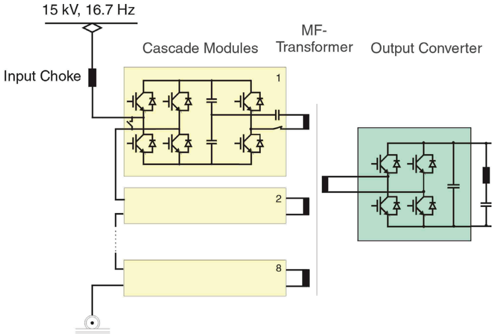
- 4Q AC-DC + resonant DC-DC
- 8 cascaded stages on primary

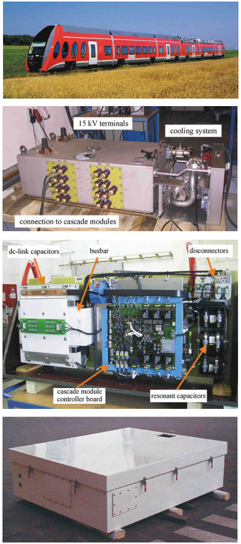
Semiconductor Devices

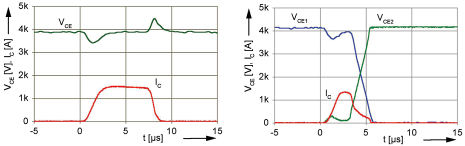
- HV side: 6.5kV IGBTs (48x)
- LV side: 3.3kV IGBTs

MFT

- Power: 1.5MW
- Frequency: 5kHz
- Core: Ferrite
- Insulation / Cooling: Oil







▲ ALSTOM reported Traction SST [3], [4]

ABB - 1.2MW POWER ELECTRONIC TRACTION TRANSFORMER - PETT_

Ratings

- Power: 1.2MW
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1800 V
- Efficiency: 95% (peak)

Topology

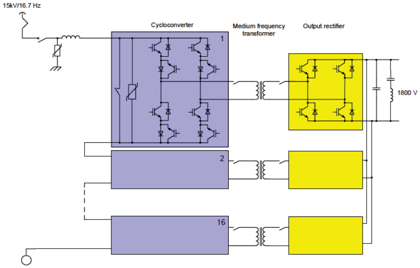
- 4Q AC-AC + AC-DC
- 16 cascaded stages

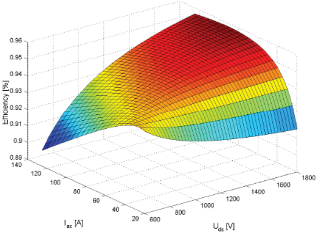
Semiconductor Devices

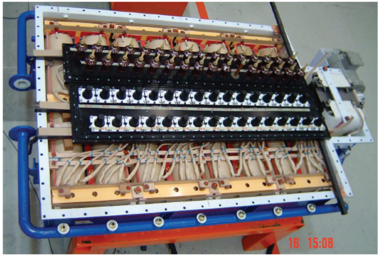
- HV side: 3.3kV IGBTs
- LV side: 3.3kV IGBTs

MFT

- Power: 75kW per MFT
- Frequency: 400Hz
- Core: SiFe
- Insulation / Cooling: oil







▲ ABB reported PETT [5]

ABB - 1.2MW PETT

Characteristics

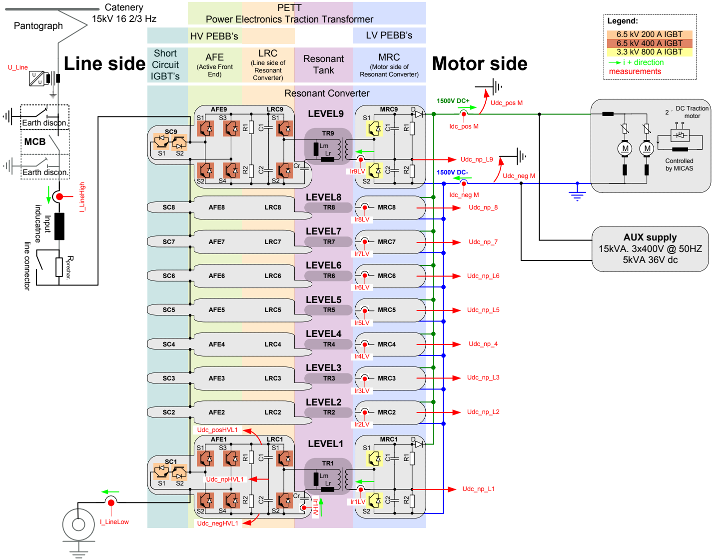
- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500 V
- 9 cascaded stages (n + 1)
- input-series output-parallel
- double stage conversion

99 Semiconductor Devices

- HV PEBB: 9 x (6 x 6.5kV IGBT)
- LV PEBB: 9 x (2 x 3.3kV IGBT)
- Bypass: 9 x (2 x 6.5kV IGBT)
- Decoupling: 9 x (1 x 3.3kV Diode)

9 MFTs

- Power: 150kW
- Frequency: 1.75kHz
- Core: Nanocrystalline
- Winding: Litz
- Insulation / Cooling: oil



▲ ABB PETT scheme [6], [7]

ABB - 1.2MW PETT DESIGN

Retrofitted to shunting locomotive

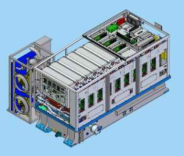
- Replaced LFT + SCR rectifier
- Propulsion motor - 450kW
- 12 months of field service
- No power electronic failures
- Efficiency around 96%
- Weight: ≈ 4.5 t

Technologies

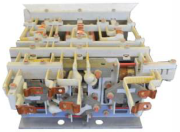
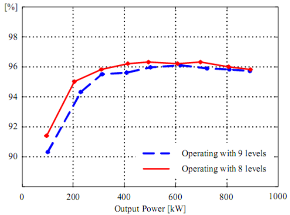
- Standard 3.3kV and 6.5kV IGBTs
- De-ionized water cooling
- Oil cooling/insulation for MFTs
- n + 1 redundancy
- IGBT used for bypass switch

Displayed at:

- Swiss Museum of Transport
- https://www.verkehrshaus.ch





▲ ABB PETT prototype [6], [7]

UTILITY SST

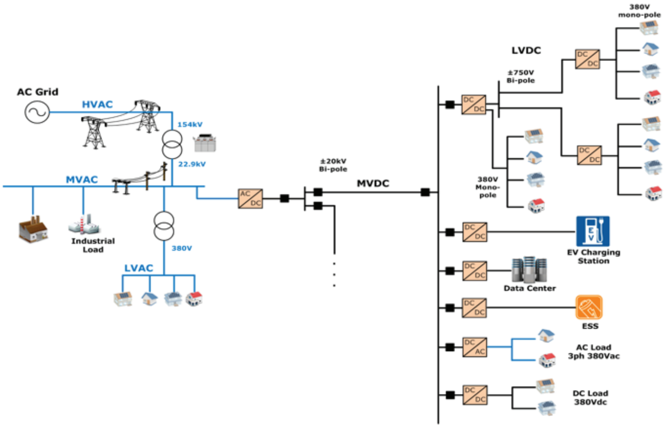
Quite different from railways

- 50 / 60 Hz grids
- Higher powers: MW, GW
- Much higher voltage: MV, HV
- High efficiency needed (> 99 %)
- High reliability needed
- High availability needed
- Weight may not be important
- Volume may not be important

Challenges

- Business case
- Cost
- Efficiency
- Reliability
- Availability

Design of a converter is the least problem!



▲ Possible future grid connections (www.english.hhi.co.kr)

UTILITY SST PROJECTS

UNIFLEX-PM

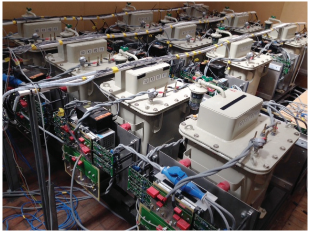
- www.eee.nott.ac.uk/uniflex/index.html
- Academic initiative
- Multiport AC-AC-AC
- Power control
- Voltage control
- Reduced scale prototypes

FREEDM

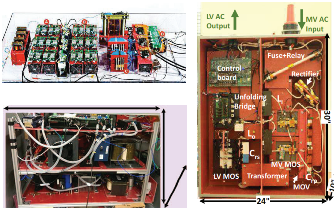
- www.freedm.ncsu.edu
- Academic initiative
- Gen-1 SST: Si-based (6.5kV, 3kHz)
- Gen-2 SST: SiC-based (15kV, 10kHz)
- Gen-3 SST: SiC-based (15kV, 40kHz)
- Reduced scale prototypes

HEART

- www.heart.tf.uni-kiel.de/en/home
- Academic initiative
- AC grids
- Energy routing
- Control features
- Reduced scale prototypes



▲ UNIFLEX-PM prototype



▲ FREEDM SSTs [8]

▲ HEART project

HUST, WUHAN - 500KVA ELECTRONIC POWER TRANSFORMER - EPT

Ratings

- Power: 500kVA
- Input AC voltage: 10kV, 50Hz
- Output AC voltage: 400V, 50Hz
- Efficiency: 93.72% (at 105 kW)
- Cost: 10x conv. transformer

Topology

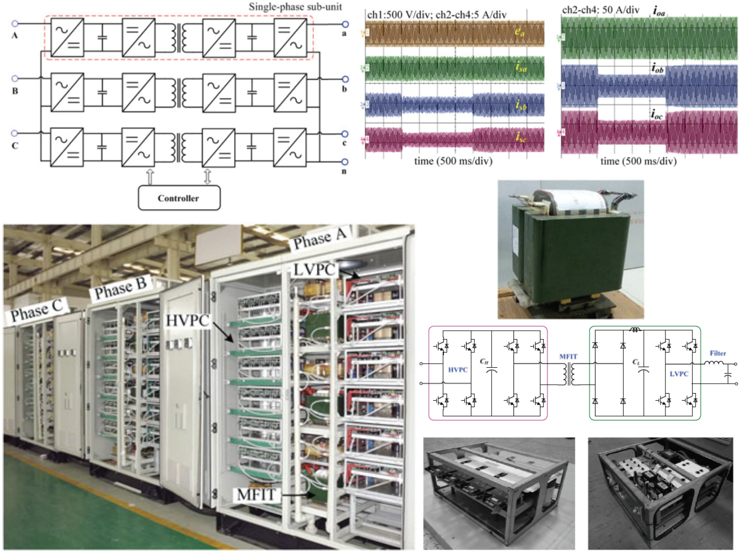
- AC-DC + DC-DC + DC-AC
- 6 cascaded stages per phase
- Unidirectional

Semiconductor Devices

- HV side: 3.3kV IGBTs
- LV side: 1.2kV IGBTs?

MFT

- Power: 30kW per MFT
- Frequency: 1kHz
- Core: Iron-based amorphous alloy
- Insulation / Cooling: solid /air



▲ HUST reported EPT [9]

SUMMARY - SOLID STATE TRANSFORMER

SST Pros

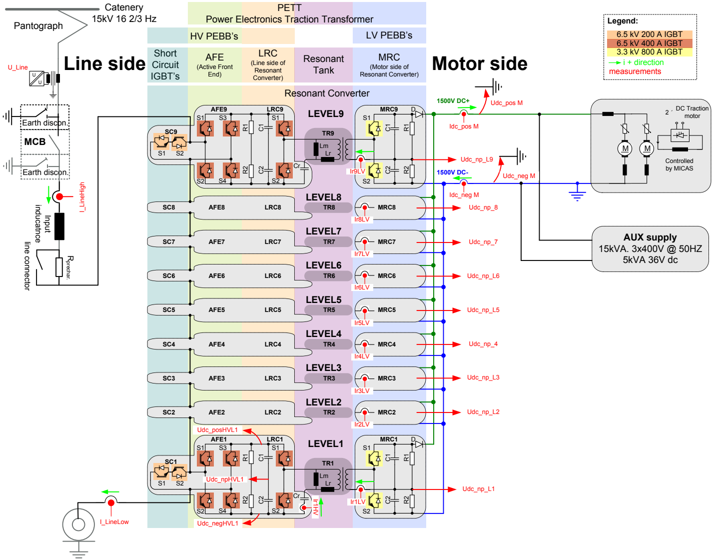
- Flexible grid interface
- AC-DC, AC-AC, DC-DC, DC-AC
- Galvanic isolation
- Advanced control features

SST Cons

- Compromised efficiency
- Increased complexity
- Higher cost
- Reliability
- Scalability

SST Future Research

- System level optimization
- Efficiency improvements
- Insulation coordination
- Protection
- MFT design optimization
- ...



▲ ABB PETT scheme: Not that simple...

MEDIUM FREQUENCY TRANSFORMERS

What are the design challenges?

MOTIVATION

- **Lower Volume** – easier system integration
- **Lower Weight** – especially important for onboard traction applications
- **Less Material** – lower investment cost, lower environmental footprint
- **Improved Efficiency** – application specific case
- **Modularity** – fractional power processing

size power

$$A_P = \frac{P_t}{K_f K_u B_m J f}$$

waveform insulation material cooling frequency

▲ Approximate transformer scaling relation

▲ Example: frequency impact on the transformer size (Prof. Akagi)

DESIGN CONSTRAINTS

Electrical [1]

- Inductance
- $B < B_{sat}$
- Turns ratio
- Duty cycle
- Frequency
- $DCR < DCR_{max}$
- $J < J_{max}$
- Leakage inductance
- Self capacitance
- Self resonance
- Skin and Proximity effects
- EMI, EMC
- Shielding
- Efficiency
- Safety
- Isolation

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

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Mechanical

- $A_{wdg} > A_{wdg-min}$
- Size (L, W, H)
- Volume
- Surface area
- Weight
- Safety
- Creepage distances
- Clearance distances
- Insulation class
- Materials
- Environmental

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

DESIGN CONSTRAINTS

Electrical [1]

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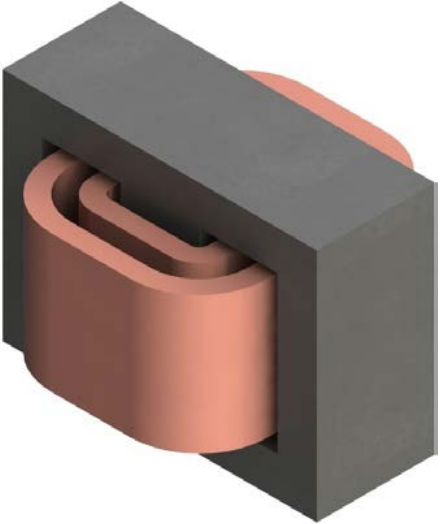
- Surface area
- Weight
- Safety
- Creepage distances
- Clearance distances
- Insulation class
- Materials
- Environmental

Thermal

- $T < T_{max}$
- $P_{wdq} < P_{wdg-max}$
- $P_{core} < P_{core-max}$
- Environmental

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

MFT SCALING LAWS



▲ Shell type MFT

MFT dimension analysis for constant B_m and J

Cooling Surface	$S_c = C_1 l^2$	k^2
Volume and Mass	$M = \gamma V = C_2 l^3$	k^3
Current	$I = JS_{Cu}$	k^2
Induced Voltage	$U = C_3 f B_m S_{Fe}$	fk^2
Apparent Power	$P = UI$	fk^4
DC Resistance	$R = N\rho l / S_{Cu}$	$1/k$
Copper Losses	$P_{Cu} = FRI^2$	$F(f)k^3$
Core Losses	$P_{Fe} = Kf^a B_m^b V$	$f^a k^3$
Temperature Rise	$\Delta\theta = (P_{Cu} + P_{Fe})/(\alpha S_c)$	$k(F(f) + f^a)$
Relative Losses	$P_r = (P_{Cu} + P_{Fe})/P$	$(F(f) + f^a)/(kf)$
Relative Cost	$\varepsilon = M/P$	$1/(kf)$

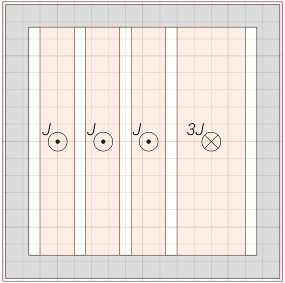
Where: F(f) - skin and proximity effect correction factor

SKIN AND PROXIMITY EFFECT

Effects

- Non-uniform current density
- Under-utilization of the conductor material
- Localized H-field distortion within the conductor volume
- Impact on conduction losses
- Impact on leakage inductance

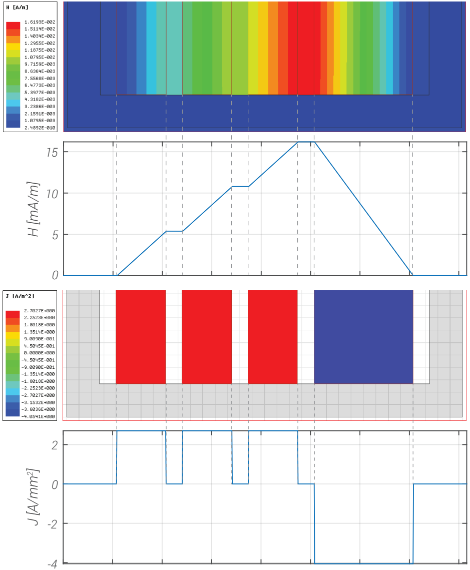
Example of the Foil Winding MFT Geometry Cross-Section



▲ Generic foil winding geometry

0.1 [Hz] (Δ = 0.01)

* Δ - the penetration ratio



▲ H and J distribution within the core window area

SKIN AND PROXIMITY EFFECT

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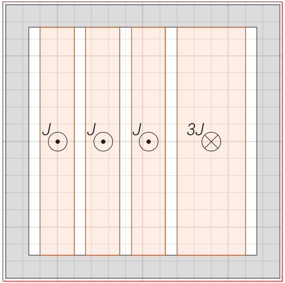
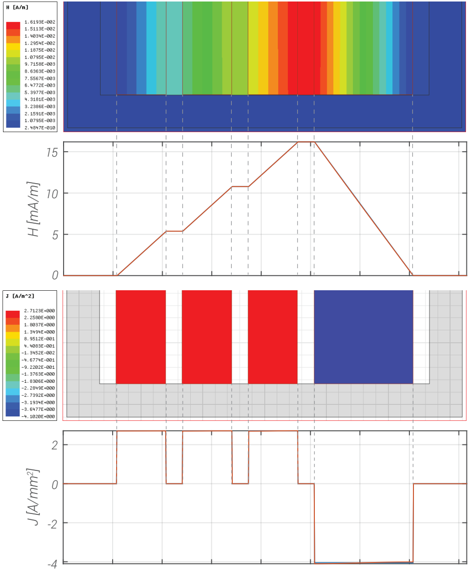


▲ Generic foil winding geometry

0.1 [Hz] (Δ = 0.01)
100 [Hz] (Δ = 0.3)

* Δ - the penetration ratio



▲ H and J distribution within the core window area

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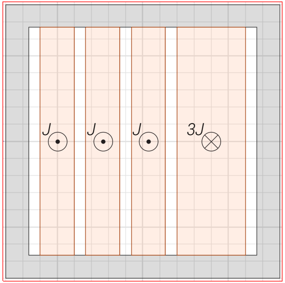
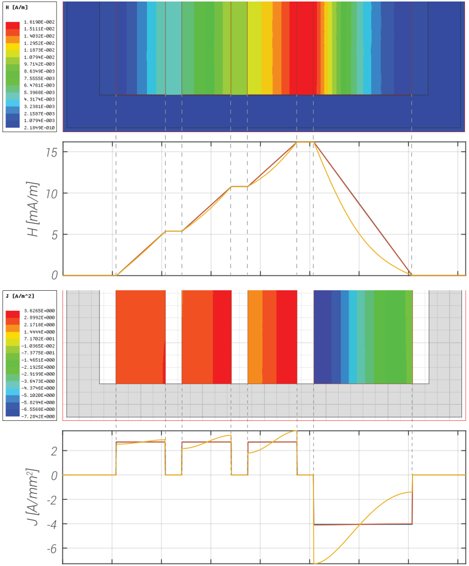


▲ Generic foil winding geometry

0.1 [Hz] (Δ = 0.01)
100 [Hz] (Δ = 0.3)
1000 [Hz] (Δ = 1)

* Δ - the penetration ratio

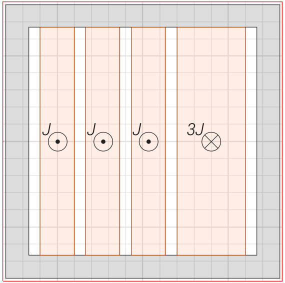


▲ H and J distribution within the core window area

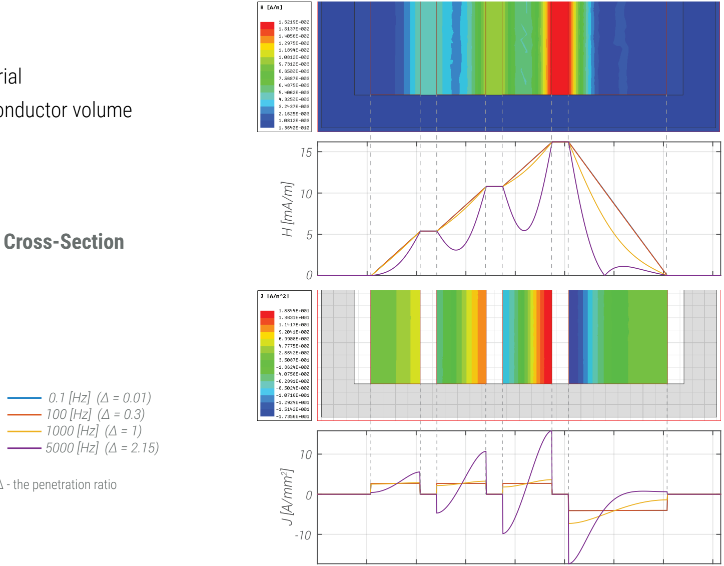
Effects

- Non-uniform current density
- Under-utilization of the conductor material
- Localized H-field distortion within the conductor volume
- Impact on conduction losses
- Impact on leakage inductance

Example of the Foil Winding MFT Geometry Cross-Section



▲ Generic foil winding geometry



* Δ - the penetration ratio

▲ H and J distribution within the core window area

SKIN AND PROXIMITY EFFECT

Effects

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- Under-utilization of the conductor material
- Localized H-field distortion within the conductor volume
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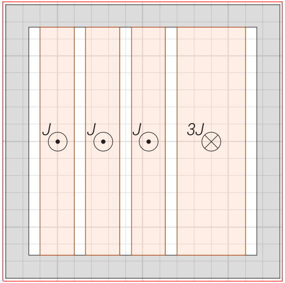
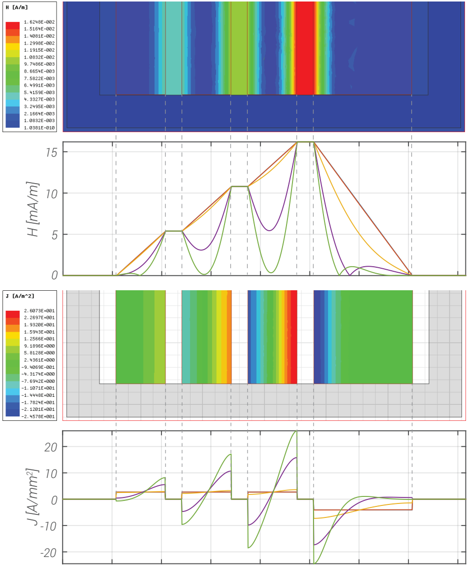
Example of the Foil Winding MFT Geometry Cross-Section



▲ Generic foil winding geometry

0.1 [Hz] (Δ = 0.01)
100 [Hz] (Δ = 0.3)
1000 [Hz] (Δ = 1)
5000 [Hz] (Δ = 2.15)
10000 [Hz] (Δ = 3)

* Δ - the penetration ratio



▲ H and J distribution within the core window area

SKIN AND PROXIMITY EFFECT

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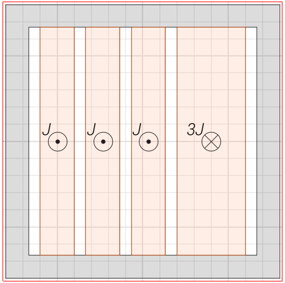
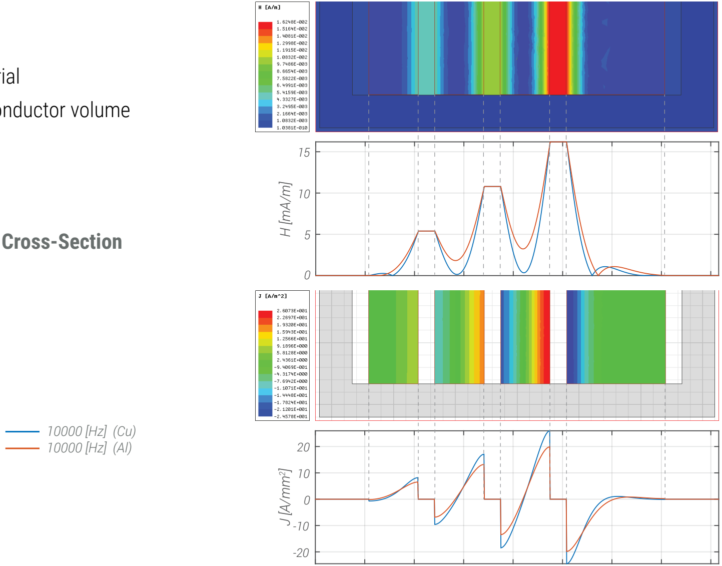
- Non-uniform current density
- Under-utilization of the conductor material
- Localized H-field distortion within the conductor volume
- Impact on conduction losses
- Impact on leakage inductance

Example of the Foil Winding MFT Geometry Cross-Section



▲ Generic foil winding geometry

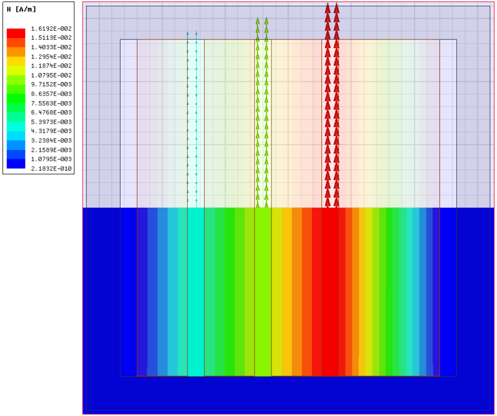


▲ H and J distribution within the core window area

EDGE EFFECT

MFT with fully filled core window height

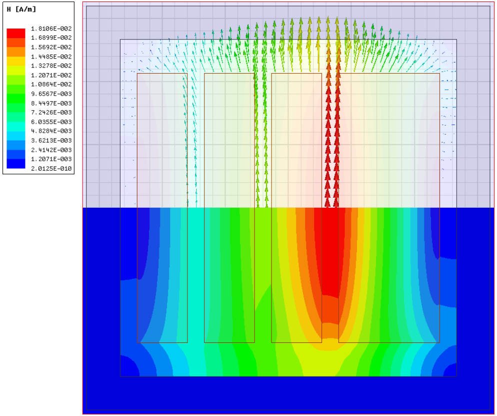
- Only H_y component exists
- H field is tangential to the foil surface



▲ Fully utilized core window height

MFT with 80% filled core window height

- Both H_x and H_y components exists
- H field is not tangential to the foil surface



▲ Partially utilized core window height

THERMAL COORDINATION

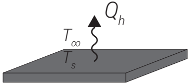
MFT Losses:

- Winding Losses
- Core Losses

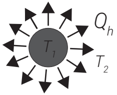
Heat Transfer Mechanisms:

- Conduction

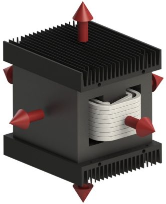
- Convection

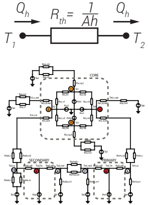


- Radiation



Qualitative Analysis:





- Heat transfer

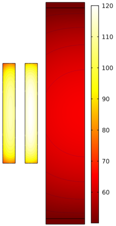
$$Q_h = hA\Delta T$$

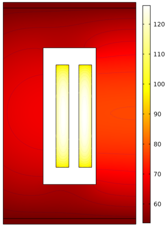
- Temperature gradient

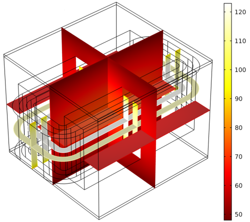
$$\Delta T = \frac{Q_h}{hA}$$

- Size decrease ($A \searrow$) implies $\Delta T \nearrow$

Temperature Distribution Example:



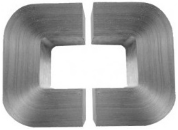




Core Materials:

- Thermal conductivity varies from $4 Wm/K$ (ferrites) to $8.35 Wm/K$ (Nanocrystalline)
- Isotropic thermal conductivity (e.g. ferrites)
- Anisotropic thermal conductivity (laminated cores e.g. Nanocrystalline)

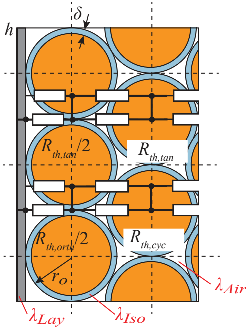
▲ Ferrite core - Isotropic



▲ Metglas core - Anisotropic

Windings:

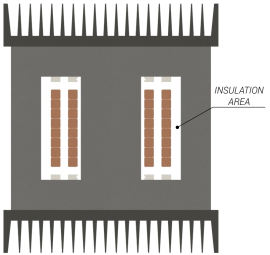
- Copper and Aluminum conductors combined with insulation
- Low R_{th} along the conductor path due low R_{th} of Cu and Al
- High R_{th} in radial direction due to layers of insulation with high R_{th}



▲ Cross section of a round wire winding [10]

Winding insulation and cooling:

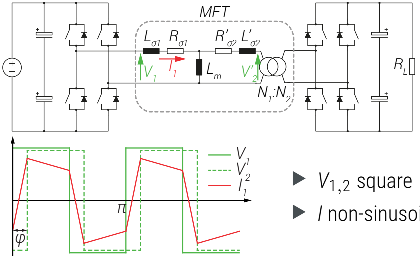
- Much higher insulation level requirement than within the winding insulation
- Good insulators have very low thermal conductivity (solid or fluid)
- Fluid based insulation provides much better cooling due to convection



▲ MFT cross section area

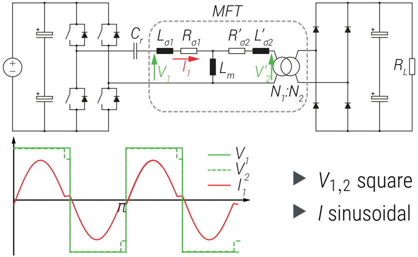
NONSINUSOIDAL VAVEFORMS

DAB Converter:



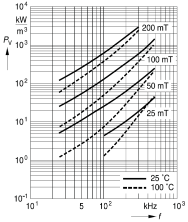
- $V_{1,2}$ square
- I non-sinusoidal

Series Resonant Converter:



- $V_{1,2}$ square
- I sinusoidal

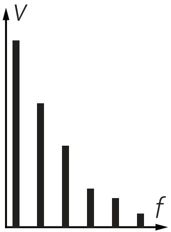
Core Losses:



▲ AC core losses

- Data-sheet data is for sinusoidal excitation
- Derived Steinmetz coefficients describe sinusoidal excitation losses
- Core is excited with square pulses
- Losses are effected
- Generalization of Steinmetz model

Winding Losses:

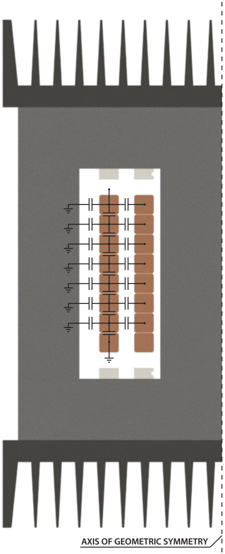


▲ Harmonics

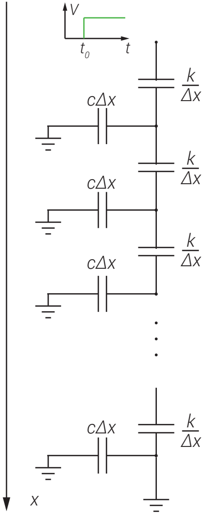
- Current waveform impacts the winding losses
- Copper is a linear material
- Losses can be evaluated in harmonic basis
- Current harmonic content must be evaluated
- Total losses are the sum of the individual harmonic losses

INSULATION COORDINATION

MFT Geometry Crossection:

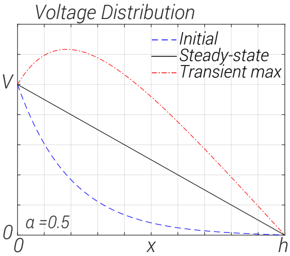


HF Winding Model:



MFT Electric Parameters:

- Parasitic capacitance cannot be neglected for HF
- Capacitances exist between turns, windings and core
- For pulse excitation voltage distribution is nonlinear
- Higher voltage gradient at the winding input than expected
- Damped oscillatory transient due to turn inductance
- Higher max voltage than expected during transient
- Need for overall insulation reinforcement
- Turn to turn insulation must especially be increased

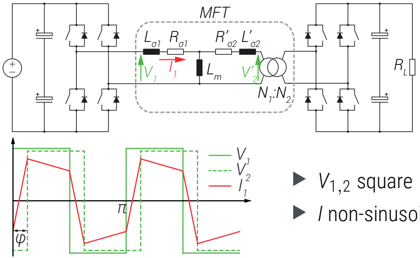


$$V(x) = V\frac{\sinh(ax)}{\sinh(ah)}$$

$$a = \sqrt{\frac{c}{k}}$$

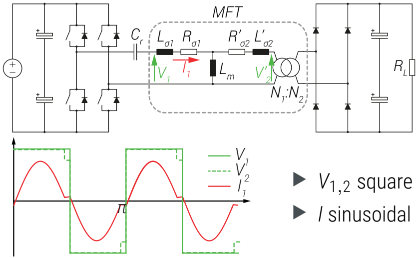
ACCURATE MFT ELECTRIC PARAMETER CONTROL

DAB Converter:



- $V_{1,2}$ square
- I non-sinusoidal

Series Resonant Converter:



- $V_{1,2}$ square
- I sinusoidal

DAB

- Leakage Inductance
- Controllability of the power flow
- Higher than $L_{\sigma.min}$:

$$L_{\sigma.min} = \frac{V_{DC1}V_{DC2}\varphi_{min}(\pi - \varphi_{min})}{2P_{out}\pi^2 f_s n}$$

- Magnetizing Inductance is normally high

SRC

- Leakage inductance is part of resonant circuit
- Must match the reference:

$$L_{\sigma.ref} = \frac{1}{\omega_0^2 C_r}$$

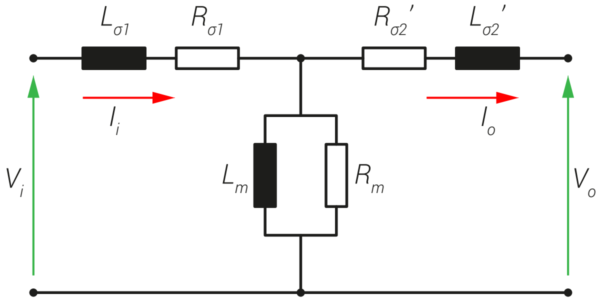
- Magnetizing inductance is normally high
- Reduced in case of LLC
- Limits the magnetization current to the reference $I_{m.ref}$
- Limits the switch-off current and losses

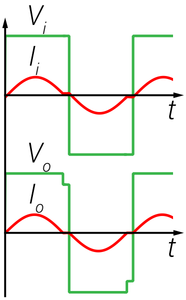
$$L_m = \frac{nV_{DC2}}{4f_s I_{m.ref}}$$

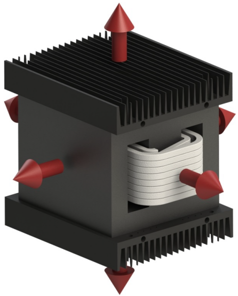
- $I_{m.ref}$ has to be sufficiently high to maintain ZVS

MFT CHALLENGES - SUMMARY

- **Skin and proximity effect losses:** impact on efficiency and heating
- **Cooling:** increase of power density $\Rightarrow$ decrease in size $\Rightarrow$ less cooling surface $\Rightarrow$ higher R_{th} $\Rightarrow$ higher temperature gradients
- **Non-sinusoidal excitation:** impact on core and winding losses and insulation
- **Insulation:** coordination and testing taking into account high $\frac{dV}{dt}$ characteristic for power electronic converters
- **Accurate electric parameter control:** especially in case of resonant converter applications







▲ left: Transformer equivalent scheme; middle: typical waveforms for resonant operation; right: MFT heat evacuation issues

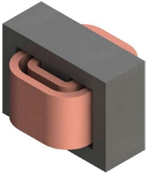
MFT Clinics

Optimize at will!

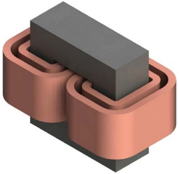
TECHNOLOGIES, MATERIALS, DESIGNS

Construction Choices:

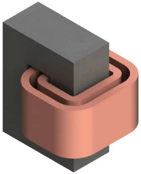
- MFT Types



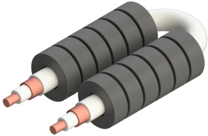
Shell Type



Core Type



C-Type

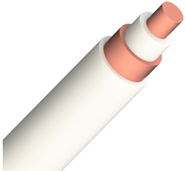


Coaxial Type

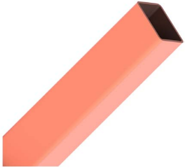
- Winding Types

Litz Wire

Foil



Coaxial



Hollow

Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites
- Windings
  - Copper
  - Aluminum
- Insulation
  - Air
  - Solid
  - Oil
- Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water

MFT HALL OF FAME

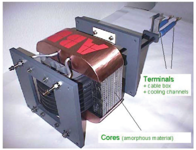


ABB: 350kW, 10kHz

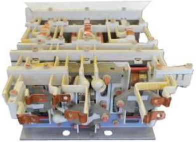
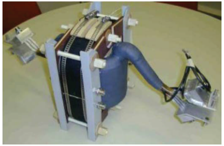
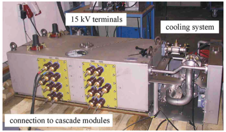


ABB: 3x150kW, 1.8kHz

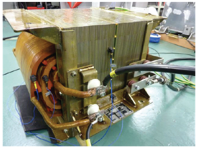


BOMBARDIER: 350kW, 8kHz

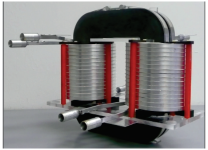


ALSTOM: 1500kW, 5kHz

IKERLAN: 400kW, 6kHz

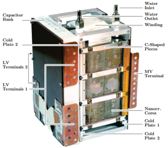


IKERLAN: 400kW, 600Hz

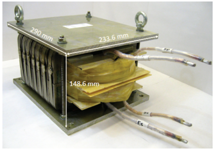


FAU-EN: 450kW, 5.6kHz

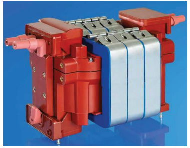
CHALMERS: 50kW, 5kHz



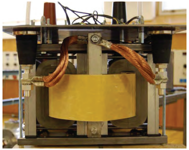
ETHZ: 166kW, 20kHz



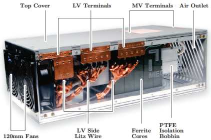
EPFL: 300kW, 2kHz



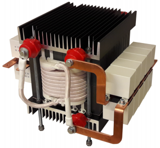
STS: 450kW, 8kHz



KTH: 170kW, 4kHz



ETHZ: 166kW, 20kHz



EPFL: 100kW, 10kHz

?

ACME: ???kW, ???kHz

ABB MFT - 2002

Construction

- Shell Type
- Coaxial winding

Electrical Ratings

- Power: 350kW
- Frequency: 10kHz
- Input Voltage: $\pm 3000V$
- Output Voltage: $\pm 3000V$

Core Material

- VAC Vitroperm 500F
- U cores

Windings

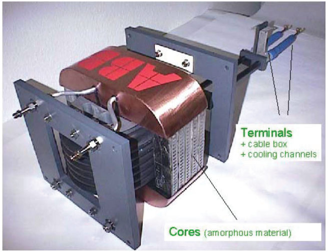
- Coaxial (Al inside, Cu outside)

Cooling

- Winding - De-ionized water
- Core - Air

Insulation

- Solid



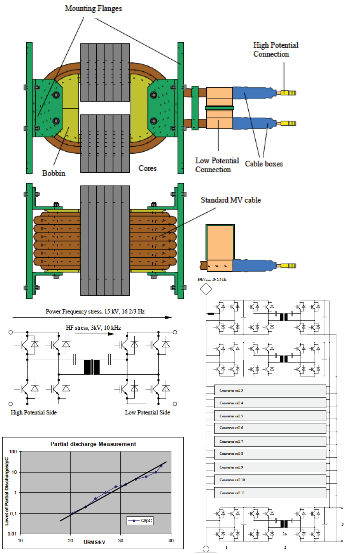
▲ 350kW MFT by ABB [11]

MFT dimensions

- Volume: $\approx$ 37 l
- V-Density: $\approx$ 9.5 kW/l
- Weight: < 50 kg
- W-Density: $\approx$ 7 kW/kg

Insulation Tests

- PD: 38kV, 50Hz, 1 min
- BIL: 95 kV (peak), 10 shots



▲ Multilevel line side converter by ABB (2002)

ALSTOM MFT - 2003

Construction
- Single core with multiple windings

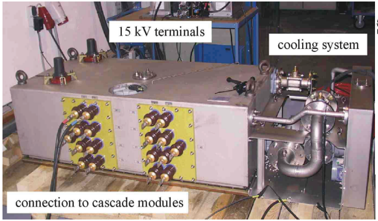
Electrical Ratings
- Power: 1.5MW
- Frequency: 5kHz
- Input Voltage: $\pm 1800V$
- Output Voltage: $\pm 1650V$

Core Material
- Ferrite
- Size and shape unclear

Windings
- Litz wire

Cooling
- Oil (MIDEL)
- Common with power electronics

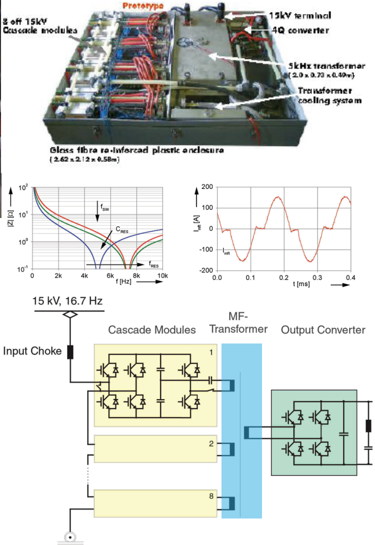
Insulation
- Oil (MIDEL)
- Immersed



▲ 1.5MW MFT by ALSTOM

MFT dimensions
- Volume: 0.72 m^3 (2.0 x 0.73 x 0.49) m
- V-Density: 2.1 kW/l
- Weight: < 1 t (estimation)
- W-Density: < 1.5 kW / kg (estimation)

e-Transformer dimensions
- (2.1 x 2.62 x 0.58) m
- Volume: 3.22 m^3
- Weight: 3.1 t (50% less)



▲ e-Transformer by ALSTOM [3], [4]

ABB MFT - 2007

Construction
- C-type

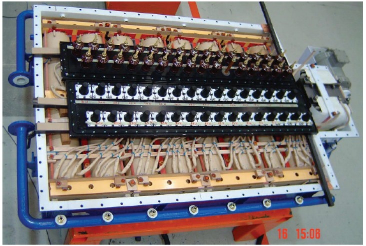
Electrical Ratings
- Power: 75kW (x16)
- Frequency: 400Hz
- Input Voltage: ±1800V
- Output Voltage: ±1800V

Core Material
- SiFe
- Custom made sheets

Windings
- Bar wire

Cooling
- Oil
- Common with power electronics

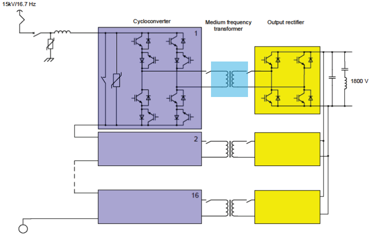
Insulation
- Oil
- Immersed



▲ Enclosure with 16 MFTs by ABB

MFT dimensions
- Volume: not reported
- V-Density: ? kW/l
- Weight: not reported
- W-Density: ? kW/kg

PETT dimensions
- Volume: 20% less
- Weight: 50% less
- Efficiency: 3% increase



▲ PETT by ABB [5]

BOMBARDIER MFT - 2007

Construction
- Core Type
- Hollow conductors

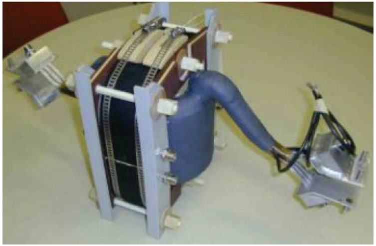
Electrical Ratings
- Power: 350kW (500kW peak)
- Frequency: 8kHz
- Input Voltage: $\pm 1000V$
- Output Voltage: $\pm 1000V$

Core Material
- Nanocrystalline
- U cores

Windings
- Hollow tubes

Cooling
- Winding - De-ionized water
- Core - Water cooled heatsink

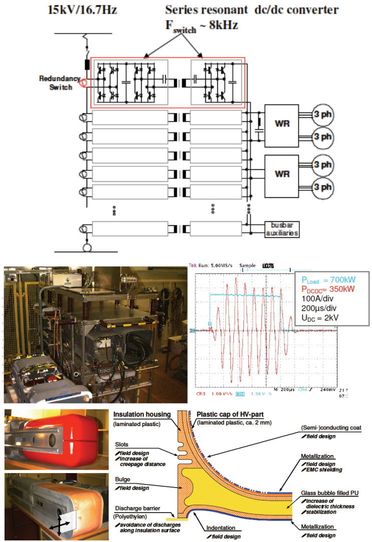
Insulation
- Solid



▲ 350kW MFT by Bombardier [12]

MFT dimensions
- Volume: not reported
- V-Density: ? kW/l
- Weight: 18 kg
- Density: ≈ 7 kW/kg

Insulation Tests
- PD: 33kV, 50Hz
- BIL: 100 kV (1.2/50)



▲ Medium frequency topology by Bombardier

ABB MFT - 2011

Construction
- C-core
- Assembly with 3 MFTs

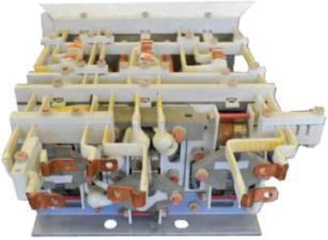
Electrical Ratings
- Power: 150kW
- Frequency: 1.75kHz
- Input Voltage: $\pm 1800V$
- Output Voltage: $\pm 750V$

Core Material
- Nanocrystalline
- C-cut cores

Windings
- Bar wire

Cooling
- Oil

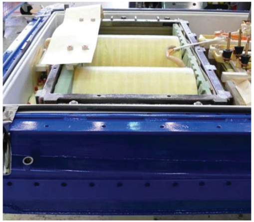
Insulation
- Oil
- Immersed

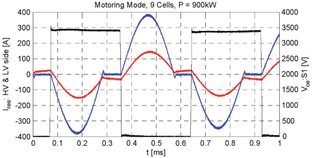


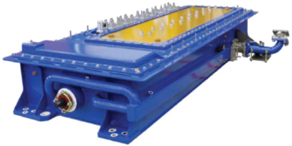
▲ 3 x 150kW MFT by ABB

MFT dimensions
- Volume: ≈ 80 l
- V-Density: ≈ 2.4 kW/l
- Weight: ≈ 170 kg
- W-Density: ≈ 1.1 kW/kg

PETT dimensions
- Weight: 4.5 t







▲ PETT tank with magnetics by ABB [6], [7]

UEN MFT - 2011

Construction
- Core Type

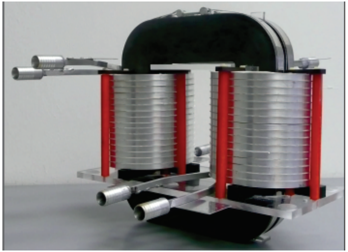
Electrical Ratings
- Power: 450kW
- Frequency: 5.6kHz
- Input Voltage: ±3600V
- Output Voltage: ±3600V

Core Material
- Nanocrystalline VITROPERM 500F
- U cores

Windings
- Aluminum
- Hollow profiles

Cooling
- Winding - de-ionized water
- Core - Oil

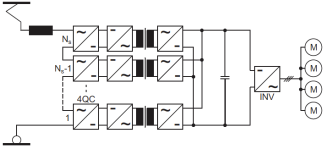
Insulation
- Oil - Immersed (primary to secondary)
- NOMEX - between turns

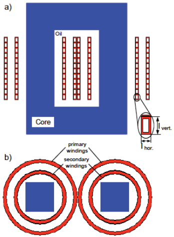


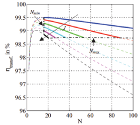
▲ 450kW MFT by UEN [13], [14], [15]

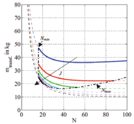
MFT dimensions
- Volume: not reported
- V-Density: ? kW/l
- Weight: 24 - 38.2 kg
- W-Density: ≈ 18.8 - 11.8 kW/kg

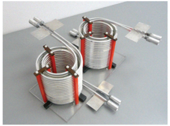
Insulation Tests
- Designed for 25kV railway lines
- PD, BIL: not reported

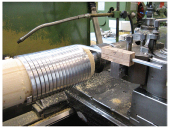












▲ MFT by UEN

ETHZ PES MFT - 2014

Construction

- Shell Type
- for the use with HC-DCM-SRC

Electrical Ratings

- Power: 166kW
- Frequency: 20kHz
- Input Voltage: $\pm 1000V$
- Output Voltage: $\pm 400V$

Core Material

- Nanocrystalline Vitroperm 500F
- C-cores

Windings

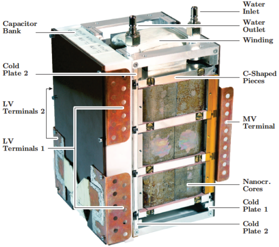
- Square Litz Wire

Cooling

- Water-cooled heat sinks

Insulation

- Solid
- Mica tape



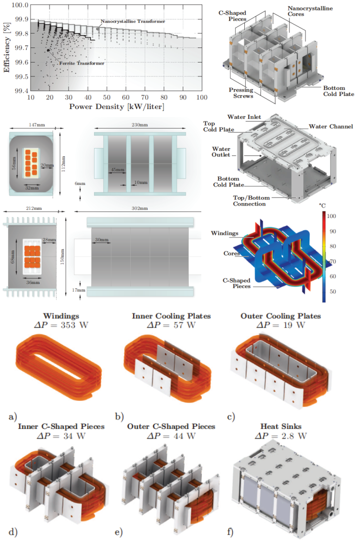
▲ 166kW MFT by ETH [16], [17], [18]

MFT dimensions

- Volume: ≈ 5 l
- V-Density: ≈ 32.7 kW/l
- Weight: ≈ 10 kg
- W-Density: ≈ 16.6 kW/kg

Insulation Tests

- No details provided



▲ Nanocrystalline MFT by ETHZ

ETHZ PES MFT - 2014 (CONT.)

Construction
- Shell Type
- for the use with TCM-DAB

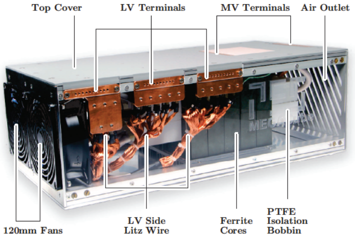
Electrical Ratings
- Power: 166kW
- Frequency: 20kHz
- Input Voltage: $\pm 750V$
- Output Voltage: $\pm 750V$

Core Material
- Ferrite N87
- U-cores U96/76/30

Windings
- Square Litz Wire

Cooling
- Winding - Forced air
- Core - Heatsinks (Forced air)

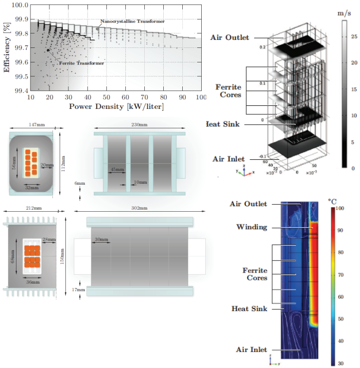
Insulation
- PTFE (teflon)

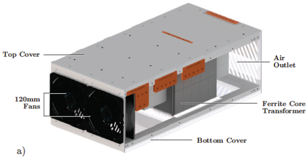


▲ 166kW MFT by ETH [16]

MFT dimensions
- Volume: ≈ 20 l
- V-Density: ≈ 8.21 kW/l
- Weight: not reported
- W-Density: not reported

Insulation Tests
- No details provided





▲ Ferrite MFT by ETHZ

STS MFT - 2015

Construction

- Core Type

Electrical Ratings

- Power: 450kW
- Frequency: 8kHz
- Input Voltage: $\pm 1800V$
- Output Voltage: $\pm 1800V$

Core Material

- Nanocrystalline
- C cores

Windings

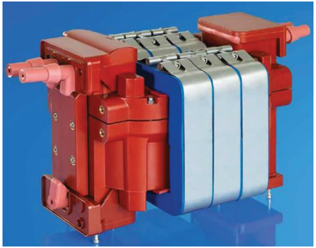
- Square Litz Wire

Cooling

- Winding - Oil
- Core - Air cooled

Insulation

- Solid combined with Oil
- Core in the air



▲ 450kW MFT by STS

MFT dimensions

- Volume: ? l
- V-Density: ≈ ? kW/l
- Weight: 50 kg
- W-Density: ≈ 9 kW/kg

Insulation Tests

- PD: 37kV, 50Hz (PD < 5pC)
- BIL: not specified

▲ MFT by STS

ABB MFT - 2017

Construction
- Core Type

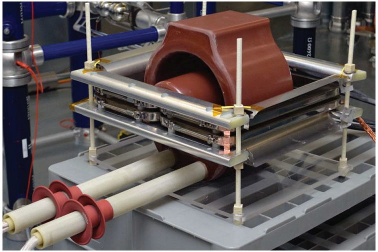
Electrical Ratings
- Power: 240kW
- Frequency: 10kHz
- Input Voltage: $\pm 600V$
- Output Voltage: $\pm 900V$

Core Material
- Nanocrystalline
- U cores (custom)

Windings
- Litz Wire (4 parallel)

Cooling
- Winding - Air
- Core - Air

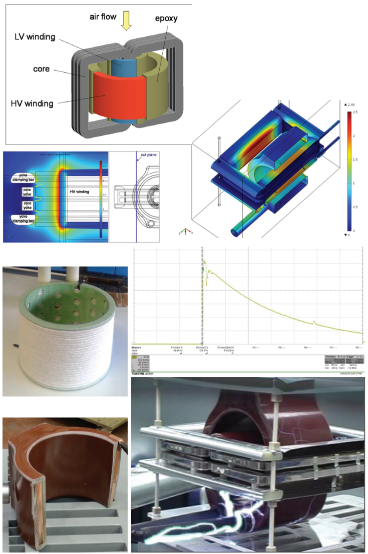
Insulation
- Solid - Cast Resin
- Air



▲ 240kW MFT by ABB [19]

MFT dimensions
- Volume: ≈ 67.7 l
- V-Density: ≈ 3.6 kW/l
- Weight: ≈ 42 kg
- W-Density: ≈ 5.7 kW/kg

Insulation Tests
- PD: 53kV, 50Hz
- BIL: 150kV



▲ MFT by ABB

ABB CERN MFT - 2017

Construction

- Core Type

Electrical Ratings

- Power: 100kW
- Frequency: 15kHz - 22kHz
- Input Voltage: $\pm 540V$
- Output Voltage: $\pm 540V$ x 24

Core Material

- Nanocrystalline
- U cores

Windings

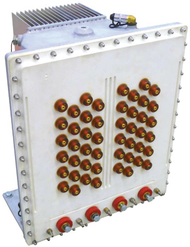
- Litz Wire

Cooling

- Winding/Core - Oil Immersed
- MFT assembly - Air

Insulation

- Oil (Ester)



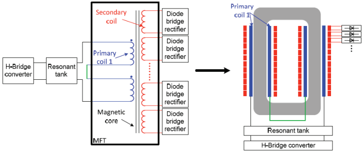
▲ 100kW MFT by ABB [20]

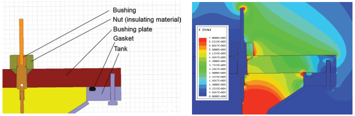
MFT dimensions

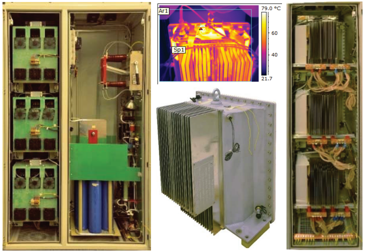
- Volume: ≈ 91 l (61 l without heatsink)
- V-Density: ≈ 1.1 kW/l
- Weight: ≈ 90 kg
- W-Density: ≈ 1.1 kW/kg

Insulation Tests

- PD: 30kV, 50Hz
- BIL: not reported







▲ MFT by ABB for CERN

EPFL PEL MFT - 2017

Construction
- Core Type

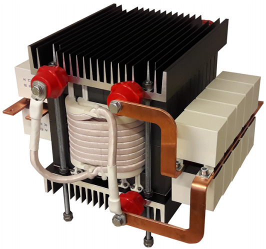
Electrical Ratings
- Power: 100kW
- Frequency: 10kHz
- Input Voltage: ±750V
- Output Voltage: ±750V

Core Material
- SiFerrite (UU9316 - CF139)
- U cores

Windings
- Square Litz Wire

Cooling
- Winding - Air
- Core - Air cooled heatsink

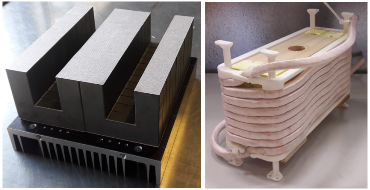
Insulation
- Air

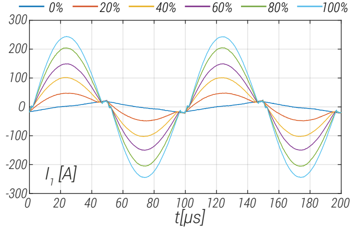


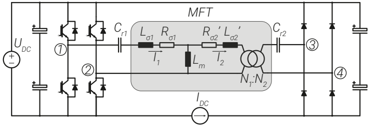
▲ 100kW MFT by EPFL [21], [22]

MFT dimensions
- Volume: ≈ 12.2 l
- V-Density: ≈ 8.2 kW/l
- Weight: ≈ 28 kg
- W-Density: ≈ 3.6 kW/kg

Insulation Tests
- PD: 6kV, 50Hz
- BIL: not performed







▲ MFT by EPFL

ETHZ PES MFT - 2018

Construction
- Shell Type
- for the use with DC-DC SRC

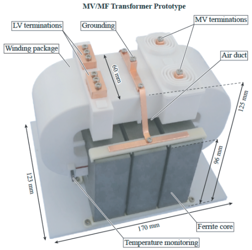
Electrical Ratings
- Power: 25kW
- Frequency: 48kHz
- Input Voltage: $\pm 3.5kV$
- Output Voltage: $\pm 400V$

Core Material
- Ferrite BFM8
- U-cores U96/60/30

Windings
- Square Litz Wire

Cooling
- Winding - Forced air
- Core - Forced air

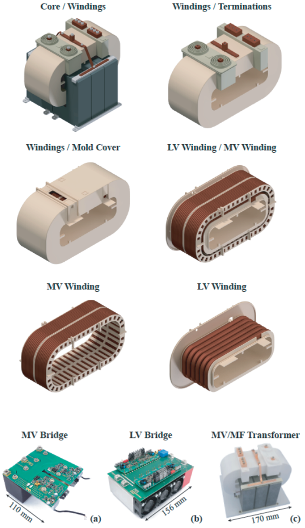
Insulation
- Dry type - Vacuum poting (windings)



▲ 25kW MFT by ETH [23]

MFT dimensions
- Volume: ≈ 3.4 l
- V-Density: ≈ 7.4 kW/l
- Weight: ≈ 6.2 kg
- W-Density: ≈ 4 kW/kg

Insulation Tests
- 20kV



▲ Ferrite MFT by ETHZ

SUMMARY - MFT DESIGNS

Variety of MFT designs

- Shell Type, Core Type, C-Type
- Copper, Aluminum
- Solid wire, Hollow conductors, Litz wire, Foil
- SiFe, Nannocrystalline, Amorphous, Ferrite

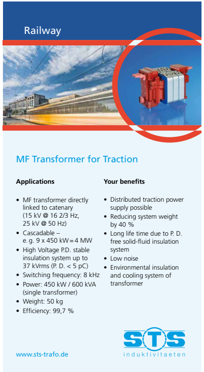
Integration with Power Electronics

- Insulation coordination
- Cooling
- Electrical parameters
- Choice of core materials
- Form factor constraints
- Optimization at the system level

Custom designs prevail

There is no best design...

Limited commercial options. Example: STS ⇒



Source/ Type	P_n kVA	Freq. kHz	U_{iso} kV	Core mat.*	Cooling method	Tran. Power density†	Eff.⋆ %	Struct./ Wind.+
GE:1992[65] Dry	50	50	N/A	Ferr.	Air	12(wt)	$99.4^{a,c}$	Coaxial/ Cable
GE:2008[66] Dry	150	10	N/A	Amor.	Air	N/A	N/A	Core/ Ro. Litz
UWM:1995[67] Dry	120	20.4	N/A	Ferr.	Water	59.5(vol)	$99.6^{a,c}$	Coaxial/ Cable
ABB:2002[43] Dry	350	10	15	Nano.	Water	>7(wt)‡	N/A	Coaxial/ Cable
ABB:2007[47] Oil	75	0.4	15	Si-Fe	Oil	N/A	$>95^{b,c}$	So. Cu
ABB:2011[50, 52] Oil	150	1.75	15	Nano.	Oil	N/A	$\approx 96^{b,c}$	Ro. Litz
KTH:2009[68] Oil	170	4	30	Amor.	Water Oil	3.45(wt)	$99^{a,c}$	Shell/ Ro. Litz Foil
TUD:2005[69, 70] Dry	50	25	N/A	Nano.	Water	≈50(vol)	$>97^{b,c}$	Shell/ Foil
Bomb:2007[30] Dry	500	8	15	Nano.	Water	27.8(wt)	N/A	Shell/ Hol. Al
FAU:2011[71] Oil	450	5.6	25	Nano.	Water Oil	N/A	N/A	Core/ Hol. Al
NCSU:2010[72]◇ Dry	10	3	15	Amor.	Air	N/A	$96.76^{a,c}$ $97.3^{a,c}$ $97.16^{a,c}$	Core/ Ro. Litz
NCSU:2012[73] Dry	30	20	9.5	Nano.	Air	N/A	$99.5^{a,d}$	Coaxial/ Ro. Litz So. Cu
EPFL:2010[8] Dry	25	2	8	Amor.	Air	2.5(vol)	$99.13^{a,d}$	Shell/ Rec. Litz
IK4:2012[74]◇ Dry	400	<1 >5	18	Si-Fe Nano.	Air Fan	3.41(vol) 14.88(vol)	$99.36^{a,d}$ $99.76^{a,d}$	Shell Core
ETH:2013[14, 23]◇ Dry	166	20	N/A	Nano. Ferr.	Water Fan	32.7(vol) 8.21(vol)	$99.5^{a,c}$ $99.4^{a,c}$	Shell/ Rec. Litz
ETH:2015[75]◇ Dry	25	25 50 83	N/A	Ferr.	Air	8.2(vol) 13.3(vol) 15.9(vol)	N/A	Matrix/ Litz
Chalm:2016[76]◇ Dry	50	5	6	Nano. Ferr.	Air Air	15.1(vol) 11.5(vol)	$99.66^{a,c}$ $99.58^{a,c}$	Shell/ Rec. Litz
STS:2014[77] Oil/Dry∇	450	8	>30	N/A	Oil Air	9(wt)	$99.7^{a,c}$	Shell/ Litz

▲ Another overview of MFTs reported in literature [24]

COFFEE BREAK

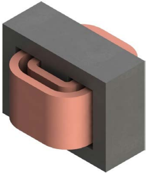
MATERIALS

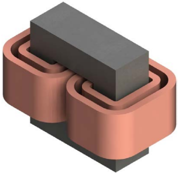
What design choices are available?

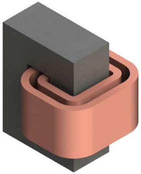
TECHNOLOGIES AND MATERIALS

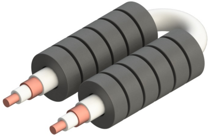
Construction Choices:

- MFT Types



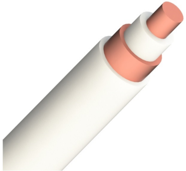


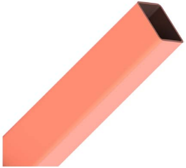




Shell Type | Core Type | C-Type | Coaxial Type

- Winding Types





Litz Wire | Foil | Coaxial | Hollow

Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites
- Windings
  - Copper
  - Aluminum
- Insulation
  - Air
  - Solid
  - Oil
- Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water

MAGNETIC MATERIALS - SILICON STEEL

Ferromagnetic - Silicon Steel

- Iron based alloy of Silicon provided as isolated laminations
- Mostly used for line frequency transformers

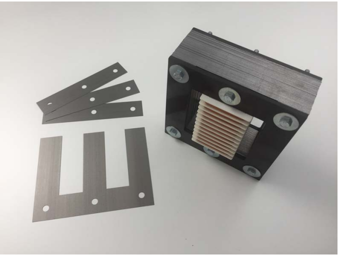
Advantages

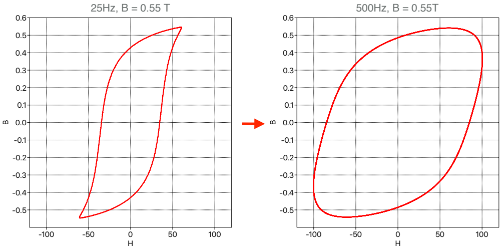
- Wide initial permeability range
- High saturation flux density
- High Curie-termpature
- Relatively low cost
- Mechanically robust
- Various core shapes available (easy to form)

Disadvantages

- High hysteresis loss (irreversible magnetisation)
- High eddy current loss (high electric conductivity)
- Acoustic noise (magnetostriction)

Saturation B	Init. permeability	Core loss (10 kHz, 0.5T)	Conductivity
0.8 ~ 2.2 T	$0.6 \sim 100 \cdot 10^3$	50 ~ 250 W/kg	$2 \cdot 10^7 \sim 5 \cdot 10^7$ S/m





▲ Example: Measured B-H curve of M330-35 laminate

MAGNETIC MATERIALS - AMORPHOUS ALLOY

Ferromagnetic - Amorphous Alloy

- Iron based alloy of Silicon as thin tape without crystal structure
- For both line frequency and switching frequency applications

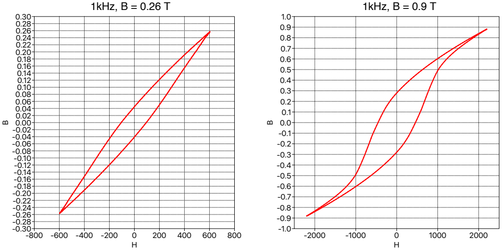
Advantages

- High saturation flux density
- Low hysteresis loss
- Low eddy current loss (low electric conductivity)
- High Curie-temperature
- Mechanically robust

Disadvantages

- Relatively narrow initial permeability range
- Very high acoustic noise (magnetostriction)
- Limited core shapes available (difficult to form)
- Relatively expensive

Saturation B	Init. permeability	Core loss (10kHz, 0.5T)	Conductivity
0.5 ~ 1.6 T	$0.8 \cdot 10^3$ ~ $50 \cdot 10^3$	2 ~ 20 W/kg	< $5 \cdot 10^3$ S/m



▲ Example: Measured B-H curve of Metglas 2605SA

MAGNETIC MATERIALS - NANOCRYSTALLINE ALLOY

Ferromagnetic - Nanocrystalline Alloy

- Iron based alloy of silicon as thin tape with minor portion of crystal structure
- For both line frequency and switching frequency applications

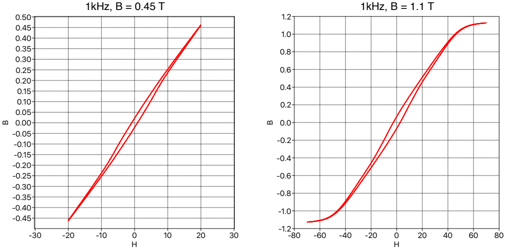
Advantages

- Relatively narrow initial permeability range
- High saturation flux density
- Low hysteresis loss
- High Curie-temperature
- Low acoustic noise

Disadvantages

- Eddy current loss (compensated thanks to the thin tape)
- Mechanically fragile
- Limited core shapes available (difficult to form)
- Relatively expensive

Saturation B	Init. permeability	Core loss (10kHz, 0.5T)	Conductivity
1 ~ 1.2 T	$0.5 \cdot 10^3 \sim 100 \cdot 10^3$	< 50 W/kg	$3 \cdot 10^3 \sim 5 \cdot 10^4$ S/m



▲ Example: Measured B-H curve of VITROPERM 500F

MAGNETIC MATERIALS - FERRITES

Ferrimagnetic - Ferrites

- Ceramic material made from powder of different oxides and carbons
- For both line frequency and switching frequency applications

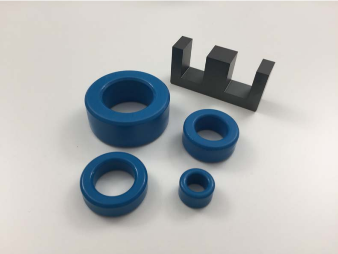
Advantages

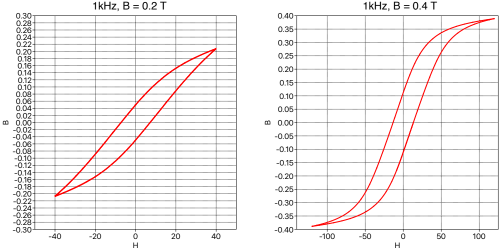
- Relatively narrow initial permeability range
- Low hysteresis loss
- Very low eddy current loss
- Low acoustic noise
- Relatively low cost
- Various core shapes available

Disadvantages

- Low saturation flux density
- Narrow range of initial permeability
- Magnetic properties deteriorate with temperature increase
- Mechanically fragile

Saturation B	Init. permeability	Core loss (10kHz, 0.5T)	Conductivity
0.3 ~ 0.5 T	$0.1 \cdot 10^3 \sim 20 \cdot 10^3$	5 ~ 100 W/kg	$< 1 \cdot 10^{-5}$ S/m





▲ Example: Measured B-H curve of Ferrite N87

MAGNETIC MATERIALS - CHARACTERIZATION

Material characterisation

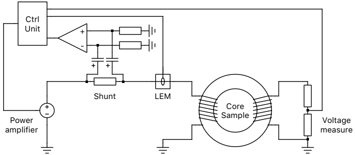
- Data sheet are often not sufficient
- Power Electronics non-sinusoidal waveforms

Calorimetric approach

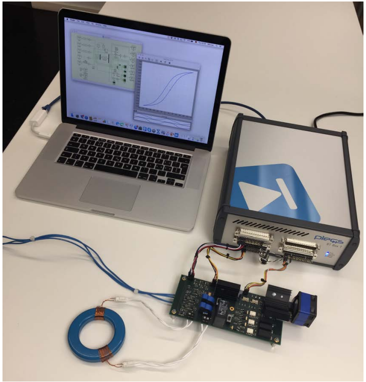
- Core sample placed in thermally isolated chamber
- Measure temperature difference between the inlet- and outlet coolant
- Time consuming and difficult to exclude winding loss

Electrical approach

- Two windings installed on the sample core
- RF Power amplifier provides sinusoidal on the primary winding
- Primary winding current sensing using shunt resistor, to obtain H
- Secondary winding voltage sensing using resistor divider, integrated to get B
- Control unit for reference signal generation and data acquisition



▲ Commercial B-H Analyser; Source: www.iti.iwatsu.co.jp/en



▲ EPFL characterisation setup for magnetic materials

WINDING MATERIALS

Copper winding

- Flat wire - low frequency, easy to use
- Litz wire - high frequency, limited bending
- Foil - provide flat windings
- Hollow tubes - provide cooling efficiency
- Better conductor
- More expensive
- Better mechanical properties

Aluminium winding

- Flat wire
- Foil - skin effect differences compared to Copper
- Hollow tubes
- Difficult to interface with copper
- Offer some weight savings
- Cheaper
- Somewhat difficult mechanical manipulations

Copper Parameters

Electrical conductivity	$58.5 \cdot 10^6\ S/m$
Electrical resistivity	$1.7 \cdot 10^{-8}\ \Omega m$
Thermal conductivity	$401\ W/mK$
TEC (from 0° to 100° C)	$17 \cdot 10^{-6}\ K^{-1}$
Density	$8.9\ g/cm^3$
Melting point	$1083\ ^\circ C$

Aluminum Parameters

Electrical conductivity	$36.9 \cdot 10^6\ S/m$
Electrical resistivity	$2.7 \cdot 10^{-8}\ \Omega m$
Thermal conductivity	$237\ W/mK$
TEC (from 0° to 100° C)	$23.5 \cdot 10^{-6}\ K^{-1}$
Density	$2.7\ g/cm^3$
Melting point	$660\ ^\circ C$

INSULATING MATERIALS

Multiple influencing factors

- Operating voltage levels
- Over-voltage category
- Environment - IP class
- Temperature
- Moisture
- Cooling implications
- Ageing (self-healing?)
- Manufacturing complexity
- Partial Discharge
- BIL
- Cost

Dielectric properties

- Breakdown voltage (dielectric strength)
- Permittivity
- Conductivity
- Loss angle
- ...

Dielectric material	Dielectric strength (kV/mm)	Dielectric constant
Air	3	1
Oil	5 - 20	2 - 5
Mica tape	60 - 230	5 - 9
NOMEX 410	18 - 27	1.6 - 3.7
PTFE	60 - 170	2.1
Mylar	80 - 600	3.1
Paper	16	3.85
PE	35 - 50	2.3
XLPE	35 - 50	2.3
KAPTON	118 - 236	3.9

▲ Variety of choices available...

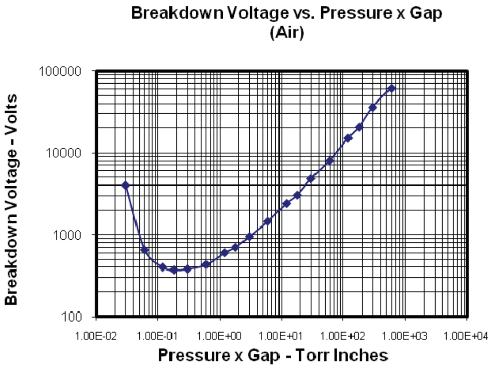
INSULATING MATERIALS - AIR

Air

- Generally good electric insulator
- Available
- Add no mass to design
- Free
- Provides cooling
- Not sufficient alone
- Additional insulation (e.g. turn-to-turn)
- Generally, not the smallest design
- Dielectric strength variation - **Pachen Law**

$$V_{BD} = \frac{Bpd}{ln(Apd) - ln\left(ln(1 + \frac{1}{\gamma_{se}})\right)}$$

- V_{BD} breakdown voltage in volts
- p - pressure in pascals
- d - gap distance in meters
- γ_{se} - secondary electron emission coef.
- A, B - parameters experimentally determined



▲ Paschen curve for air

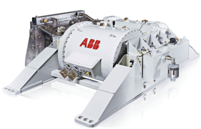
INSULATING MATERIALS - OIL

Oil

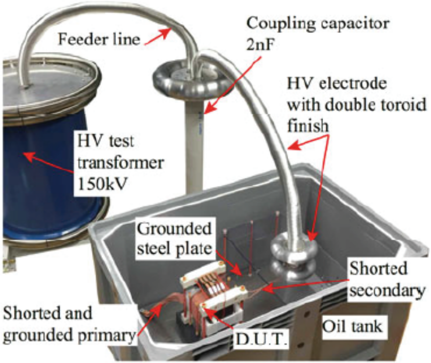
- In use for a very long time
- Excellent insulating properties
- Good thermal conductivity
- High voltage transformers
- Insulate and cool at the same time
- Natural or forced convection
- Self-healing (PD)
- Environmental concerns

Challenges

- Not a power electronics technology
- Integration issues
- Thermal expansion
- Forced convection - need for pumo
- Flammability (mineral oils)
- Adds weight to the design
- Oil degradation



▲ left: Distribution oil transformer; right: New traction oil transformer; www.abb.com



▲ Oil insulated HFT PD testing [25]

INSULATING MATERIALS - SOLID

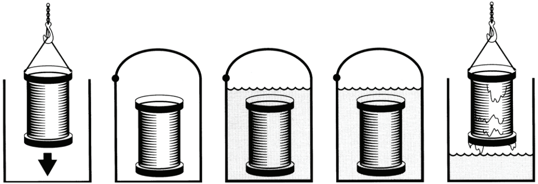
Solid Insulation

- Dry Type designs
- Vacuum-Pressure Impregnation (VPI)
- Vacuum-immersion (resin-encapsulated)
- Vacuum-fill (solid-cast)
- Variety of resin mixtures available
- Need for specialized equipment

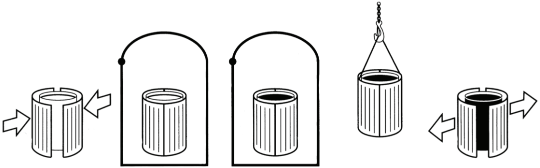
Challenges

- Direct impact on thermal design
- Adds weight to the design
- Ageaing uncertainty
- Mixed frequency stress
- Partial Discharge
- Mechanical strength - cracks
- CTI - Creepage distances

▲ left: www.sts-trafo.com; right: www.siemens.com



▲ Resin-Encapsulated transformer winding (www.schneider-electric.com)



▲ Solid-Cast transformer winding (www.schneider-electric.com)

SUMMARY - TECHNOLOGIES AND MATERIALS

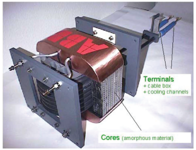


ABB: 350kW, 10kHz

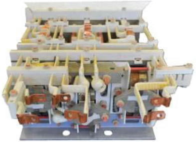
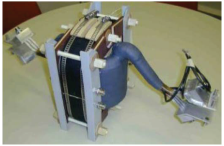
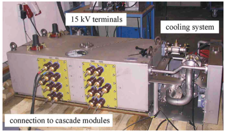


ABB: 3x150kW, 1.8kHz

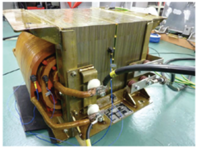


BOMBARDIER: 350kW, 8kHz

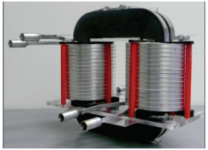


ALSTOM: 1500kW, 5kHz

IKERLAN: 400kW, 6kHz

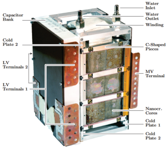


IKERLAN: 400kW, 600Hz

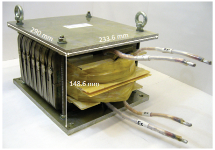


FAU-EN: 450kW, 5.6kHz

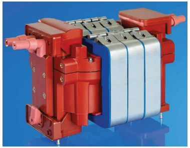
CHALMERS: 50kW, 5kHz



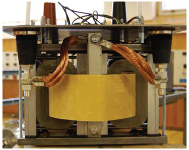
ETHZ: 166kW, 20kHz



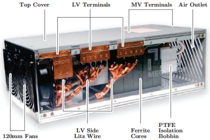
EPFL: 300kW, 2kHz



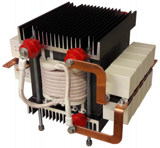
STS: 450kW, 8kHz



KTH: 170kW, 4kHz



ETHZ: 166kW, 20kHz



EPFL: 100kW, 10kHz

?

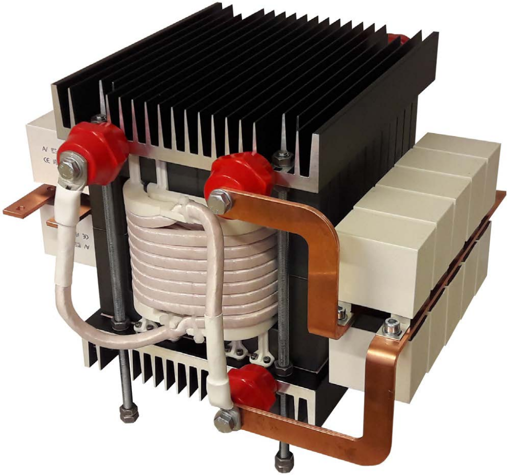
ACME: ???kW, ???kHz

MFT MODELING

The underlying analytical descriptions?

MODELING: RELEVANT EFFECTS

- Core Losses
- Winding Losses
- Leakage Inductance
- Magnetizing Inductance
- Thermal Model



MODELING: CORE LOSSES

Different core loss models:

- Based on characterization of magnetic hysteresis [26], [27], [28]
- Based on loss separation [29]
- Time domain core loss model [30]
- Based on Steinmetz Equation (MSE [31], IGSE [32], iIGSE [33])

Original Steinmetz Equation:

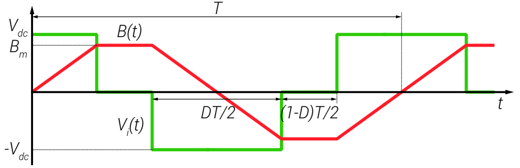
$$P_c = Kf^{\alpha}B_m^{\beta}$$

Improved Generalized Steinmetz Equation (IGSE):

$$P_c = \frac{1}{T}\int_0^T k_i\left|\frac{dB(t)}{dt}\right|^{\alpha}(\Delta B)^{\beta-\alpha}dt$$

$$k_i = \frac{K}{(2\pi)^{\alpha-1}\int_0^{2\pi}|cos(\theta)|^{\alpha}2^{\beta-\alpha}d\theta}$$

Characteristic Waveform:



$$\left|\frac{dB(t)}{dt}\right| = \begin{cases} 0 & \text{for } (1-D)T \\ \frac{2\Delta B}{DT} & \text{for } DT \end{cases}$$

Application of IGSE on the Characteristic Waveform:

$$P_s = 2^{\alpha+\beta}k_i f^{\alpha}B_m^{\beta}D^{1-\alpha}$$

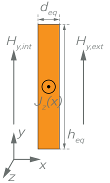
$$k_i = \frac{K}{2^{\beta-1}\pi^{\alpha-1}\left(0.2761 + \frac{1.7061}{\alpha+1.354}\right)}$$

MODELING: WINDING LOSSES

Foil Winding Electromagnetic Field Analysis:

- Dowell foil winding loss model [34]
- Porosity factor validity analysis [35], [36]
- Round wire winding loss model [37]
- ...

Foil Winding Electromagnetic Field Analysis:



$$H_y = H_{ext}\frac{\sinh(ax)}{\sinh(ad_{eq})} - H_{int}\frac{\sinh(a(x-d_{eq}))}{\sinh(ad_{eq})}$$

$$J_z = aH_{ext}\frac{\cosh(ax)}{\sinh(ad_{eq})} - aH_{int}\frac{\cosh(a(x-d_{eq}))}{\sinh(ad_{eq})}$$

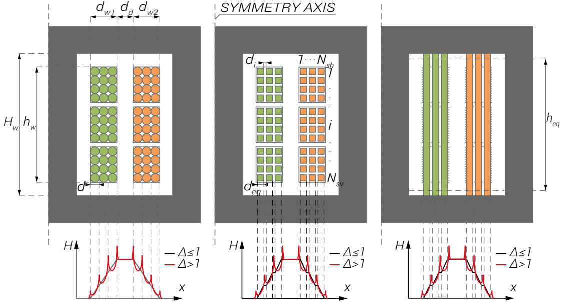
$$a = \frac{1+j}{\delta}; \qquad \delta = \sqrt{\frac{\rho}{\pi\mu f}};$$

Foil Winding Loss Calculation:

$$P_\sigma = \frac{1}{\sigma}\int JJ^* dv; \qquad P_\sigma = I^2\frac{L_w}{\delta\sigma h_w}m\left[\varsigma_1 + \frac{2}{3}(m^2-1)\varsigma_2\right];$$

$$\varsigma_1 = \frac{\sinh(2\Delta)+\sin(2\Delta)}{\cosh(2\Delta)-\cos(2\Delta)}; \quad \varsigma_2 = \frac{\sinh(\Delta)-\sin(\Delta)}{\cosh(\Delta)+\cos(\Delta)}; \quad \Delta = \frac{d_{eq}}{\delta};$$

Winding Equivalence:



$$d_{eq} = d\sqrt{\frac{\pi}{4}}; \qquad d_i = \frac{d_w - N_{sh}d_{eq}}{N_{sh}-1}; \qquad m = N_{sh};$$

$$N_{sh} = \sqrt{\frac{N_s}{K_w}}; \qquad N_{sv} = \sqrt{K_w N_s};$$

$$K_w = \frac{h_w}{d_w}$$

$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq}\frac{N_{sv}}{H_w};$$

Application of Dowell's Model on the Equivalent Foil Winding:

$$L_\sigma = N_1^2 \mu_0 \frac{l_w}{H_w} \Bigg[\underbrace{\frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2}}_{\text{Frequency dependent portion due to the magnetic energy within the copper volume of the windings}}$$

$$+ \underbrace{d_d}_{\text{Portion due to magnetic energy within the inter-winding dielectric volume}}$$

$$+ \underbrace{d_{w1i} \frac{(m_{w1}-1)(2m_{w1}-1)}{6m_{w1}}}_{\text{Portion due to magnetic energy within the inter-layer dielectric of the primary winding}}$$

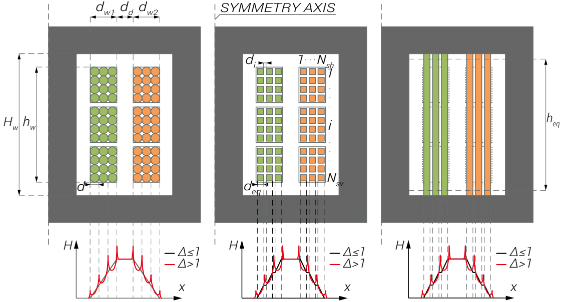
$$+ \underbrace{d_{w2i} \frac{(m_{w2}-1)(2m_{w2}-1)}{6m_{w2}}}_{\text{Portion due to magnetic energy within the inter-layer dielectric of the secondary winding}} \Bigg]$$

where:

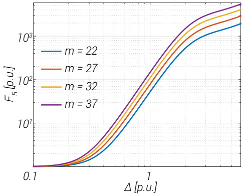
$$F_w = \frac{1}{2m^2\Delta} \left[(4m^2-1)\varphi_1 - 2(m^2-1)\varphi_2 \right]$$

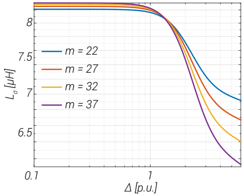
$$\varphi_1 = \frac{sinh(2\Delta) - sin(2\Delta)}{cosh(2\Delta) - cos(2\Delta)}; \qquad \varphi_2 = \frac{sinh(\Delta) - sin(\Delta)}{cosh(\Delta) - cos(\Delta)};$$

Winding Equivalence:



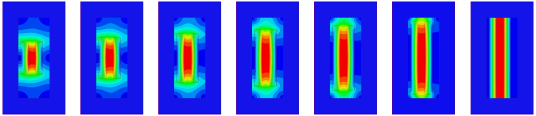
$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq}\frac{N_{sv}}{H_w}; \qquad m = N_{sh}; \qquad d_i = \frac{d_w - N_{sh} d_{eq}}{N_{sh} - 1};$$

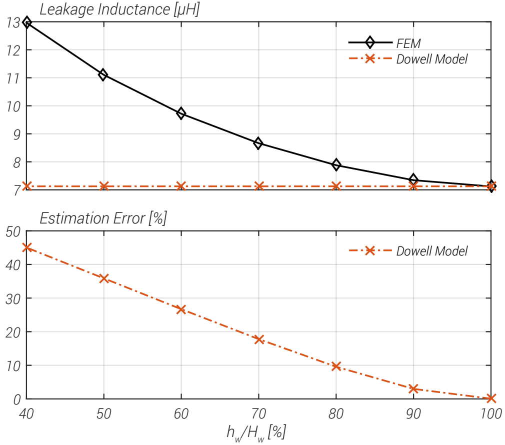




MODELING: LEAKAGE INDUCTANCE (HYBRID MODEL)

Influence of Winding Geometry on Leakage inductance:





Hybrid Leakage Inductance Model [38]:

- Rogowski correction factor:

$$h_{eq} = \frac{h_w}{K_R}$$

$$K_R = 1 - \frac{1 - e^{-\pi h_w/(d_{w1}+d_d+d_{w2})}}{\pi h_w/(d_{w1} + d_d + d_{w2})}$$

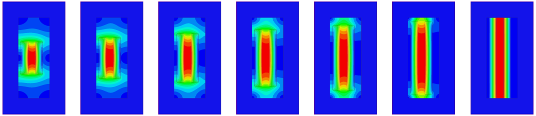
- Correction of Dowell's model ($H_w \rightarrow h_{eq}$):

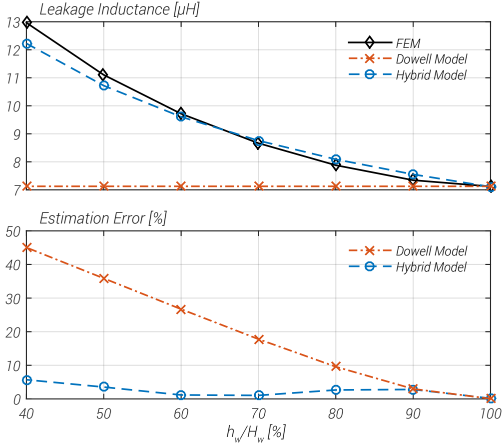
$$L_\sigma = N_1^2 \mu_0 \frac{l_w}{H_w} \left[\frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2} + d_d + d_{w1i} \frac{(m_{w1}-1)(2m_{w1}-1)}{6m_{w1}} + d_{w2i} \frac{(m_{w2}-1)(2m_{w2}-1)}{6m_{w2}} \right]$$

$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq} \frac{N_{sv}}{H_w};$$

MODELING: LEAKAGE INDUCTANCE (HYBRID MODEL)

Influence of Winding Geometry on Leakage inductance:





Hybrid Leakage Inductance Model [38]:

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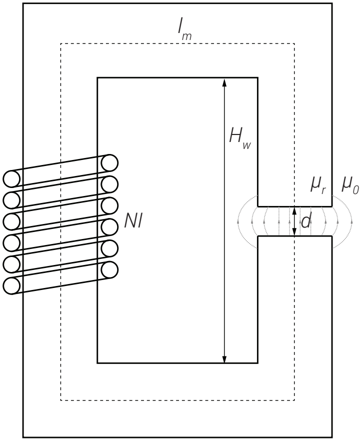
$$L_\sigma = N_1^2 \mu_0 \frac{l_w}{h_{eq}} \left[\frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2} + d_d + d_{w1i} \frac{(m_{w1}-1)(2m_{w1}-1)}{6m_{w1}} + d_{w2i} \frac{(m_{w2}-1)(2m_{w2}-1)}{6m_{w2}} \right]$$

$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq} \frac{N_{sv}}{h_{eq}};$$

MODELING: MAGNETIZING INDUCTANCE

Magnetic Circuit with an Air-Gap:



Magnetizing Inductance Calculation:

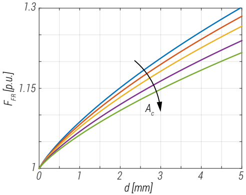
$$L_m = \frac{\mu_0 N^2 A_c}{\frac{l_m}{\mu_r} + d}$$

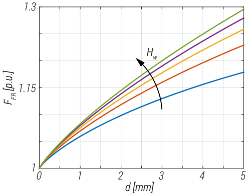
Air-Gap Calculation:

$$d = \mu_0 \frac{N^2 A_c}{L_m} - \frac{l_m}{\mu_r}$$

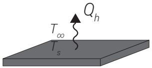
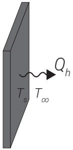
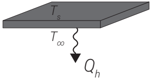
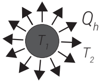
Fringing Effect:

$$L_m' = L_m F_{FR}; \qquad F_{FR} = 1 + \frac{d}{\sqrt{A_c}} ln\left(\frac{2H_w}{d}\right);$$





MODELING: HEAT-TRANSFER MECHANISMS

Conduction	$Q_h = kA\frac{\Delta T}{L}$				
Convection over Hot-Plate	$Q_h = hA(T_s - T_\infty)$	Top:		$h = \frac{k(0.65+0.36R_{a_L}^{1/6})^2}{L}$	$L = \frac{\text{Area}}{\text{Perimeter}}$
		Side:		$h = \frac{k}{L}\left(0.825 + \frac{0.387R_{a_L}^{1/6}}{\left(1+(0.492/P_r)^{9/16}\right)^{8/27}}\right)^2$	$L = \text{Height}$
		Bottom:		$h = \frac{k0.27R_{a_L}^{1/4}}{L}$	$L = \frac{\text{Area}}{\text{Perimeter}}$
Radiation	$Q_h = hA(T_1 - T_2)$			$h = \varepsilon\sigma\frac{(T_1+273.15)^4-(T_2+273.15)^4}{(T_1-T_2)}$	

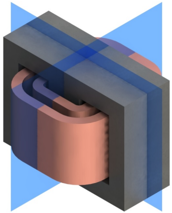
where: Ra_L - Rayleigh number, P_r - Prandtl number, ε - Emissivity, σ - Stefan–Boltzmann constant [39], [40], [41]

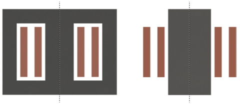
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

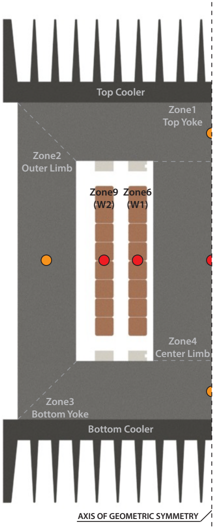
- Conduction
- Convection
- Radiation

Planes of Symmetry:

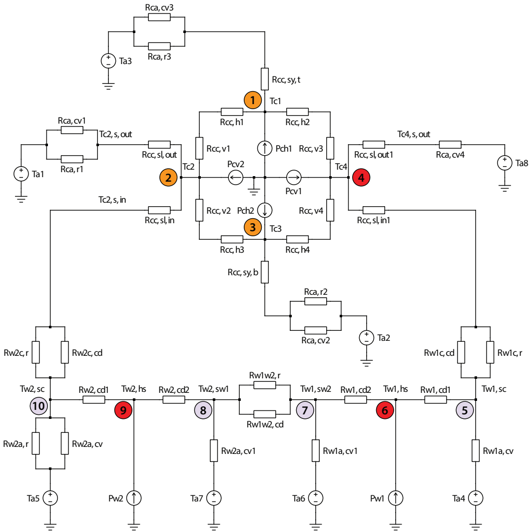




Partitioning Into Zones:



Detailed Thermal Network Model [22]:

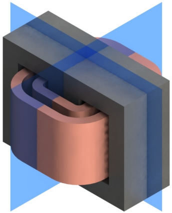


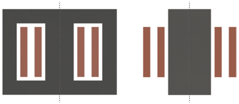
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

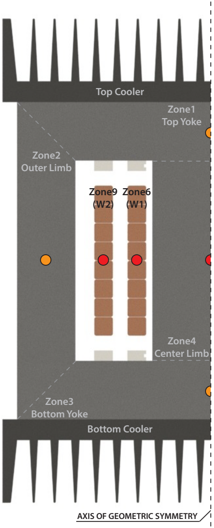
- Conduction
- Convection
- Radiation

Planes of Symmetry:





Partitioning Into Zones:



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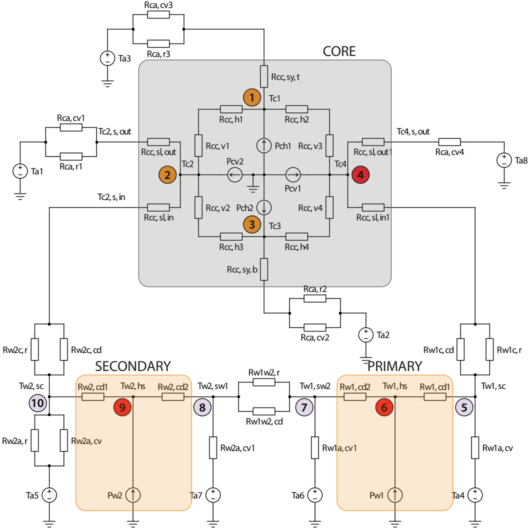
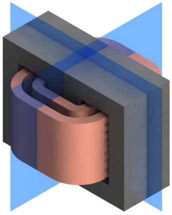


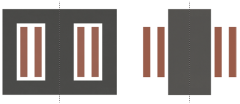
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

- Conduction
- Convection
- Radiation

Planes of Symmetry:





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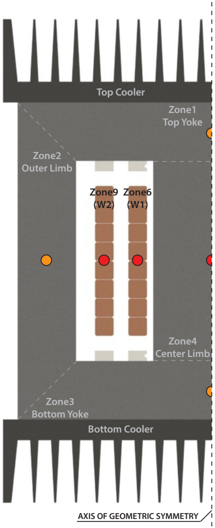
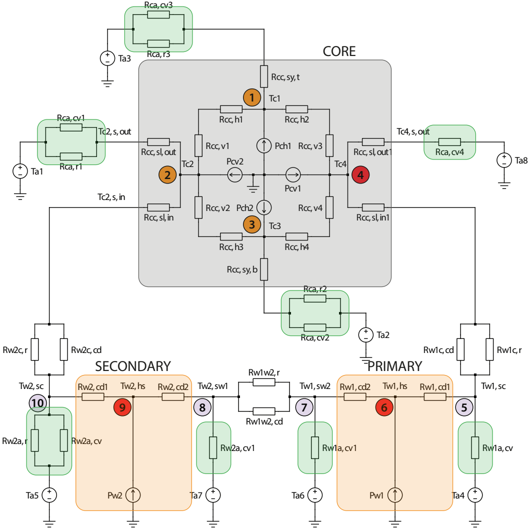


Detailed Thermal Network Model [22]:

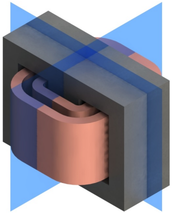


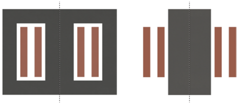
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

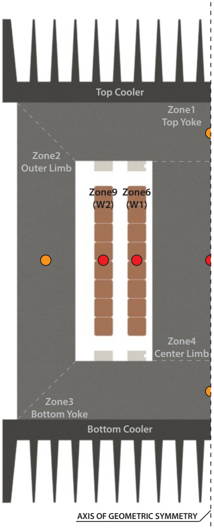
- Conduction
- Convection
- Radiation

Planes of Symmetry:

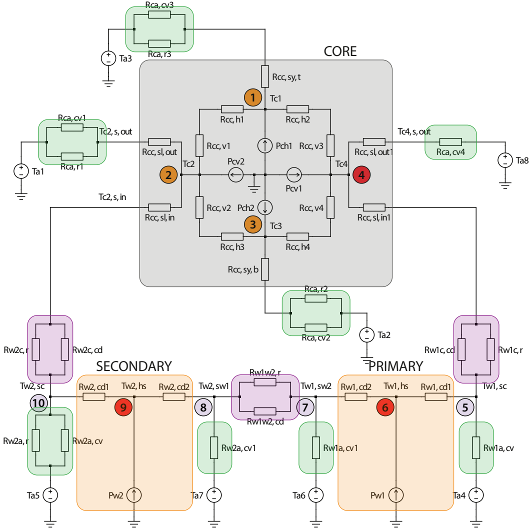




Partitioning Into Zones:



Detailed Thermal Network Model [22]:



MODELING: THERMAL MODEL IMPLEMENTATION

Implementation of Thermal Network Model:

- Admittance Matrix:

$$Q_{(n)} = Y_{th_{(n \times n)}} \Delta T_{(n)}$$

- Rearranging the nodes:

$$\begin{bmatrix} Q_{A_{(m)}} \\ 0_{(p)} \end{bmatrix} = \begin{bmatrix} Y_{thAA_{(m \times m)}} & Y_{thAB_{(m \times p)}} \\ Y_{thBA_{(p \times m)}} & Y_{thBB_{(p \times p)}} \end{bmatrix} \begin{bmatrix} \Delta T_{A_{(m)}} \\ \Delta T_{B_{(p)}} \end{bmatrix}$$

- Kron reduction:

$$\Delta T_{A_{(m)}} = \left(Y_{thAA_{(m \times m)}} - Y_{thAB_{(m \times p)}} Y_{thBB_{(p \times p)}}^{-1} Y_{thBA_{(p \times m)}} \right)^{-1} Q_{A_{(m)}}$$

$$\Delta T_{A_{(m)}} = Y_{Kron_{(m \times m)}}^{-1} Q_{A_{(m)}}$$

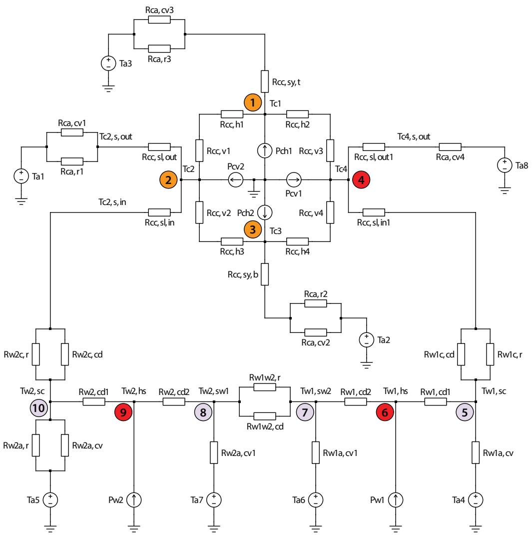
- Kron matrix:

$$Y_{Kron_{(m \times m)}} = Y_{thAA_{(m \times m)}} - Y_{thAB_{(m \times p)}} Y_{thBB_{(p \times p)}}^{-1} Y_{thBA_{(p \times m)}}$$

Analytical Model Results for the optimal MFT prototype:

T_1 [^oC]	T_2 [^oC]	T_3 [^oC]	T_4 [^oC]	T_6 [^oC]	T_9 [^oC]
51.3	59.9	58.4	73.75	124.6	116.3

Detailed Thermal Network Model [22]:



MODELING: THERMAL FEM ANALYSIS

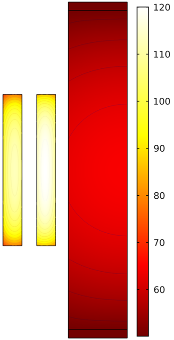
Results:

- Different cooling conditions inside and outside of core window
- High thermal conduction equalizes the temp along the conductors
- Full 3D model estimations correlate well with analytical ones

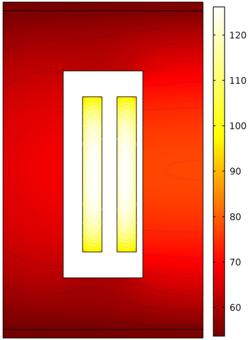
Hot-Spot Temperature Estimation Comparison:

Hot-spot nodes	$T_1\ [^oC]$	$T_2\ [^oC]$	$T_3\ [^oC]$	$T_4\ [^oC]$	$T_6\ [^oC]$	$T_9\ [^oC]$
FEM 2D detail 1	/	/	/	70	120	106
FEM 2D detail 2	/	/	/	76	127	125
FEM 3D full	/	/	/	75	122	113
Analytical	51.3	59.9	58.4	73.75	124.6	116.3

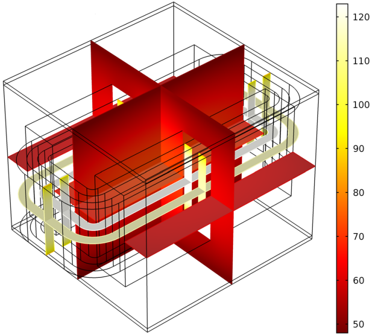
2D symmetry detail 1:



2D symmetry detail 2:



Full 3D model:



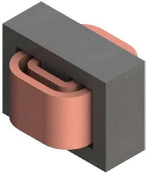
MFT DESIGN OPTIMIZATION

Brute force academic example?

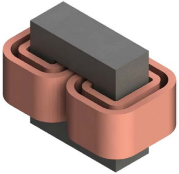
TECHNOLOGIES AND MATERIALS

Construction Choices:

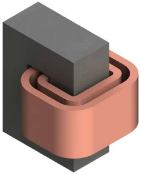
- MFT Types



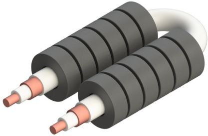
Shell Type



Core Type



C-Type

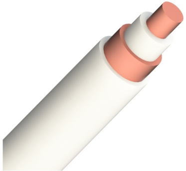


Coaxial Type

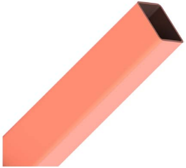
- Winding Types

Litz Wire

Foil



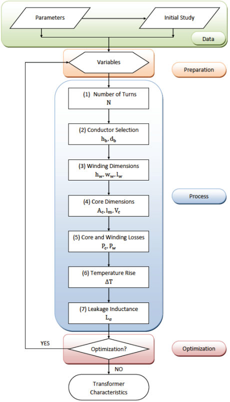
Coaxial



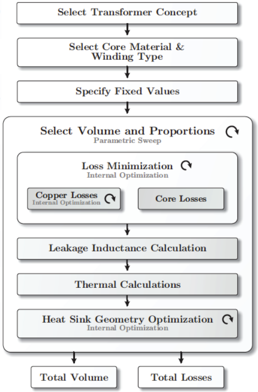
Hollow

Materials:

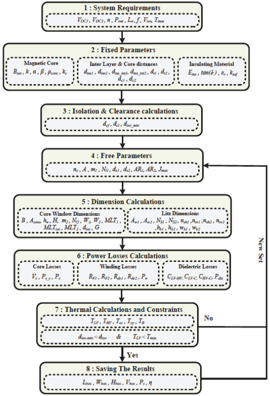
- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - **Ferrites**
- Windings
  - **Copper**
  - Aluminum
- Insulation
  - **Air**
  - Solid
  - Oil
- Cooling
  - **Air natural**/forced
  - Oil natural/forced
  - Water



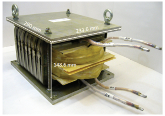
EPFL PhD: Villar [42]



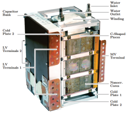
ETHZ PhD: Ortiz [16]



CHALMERS PhD: Bahmani [43]



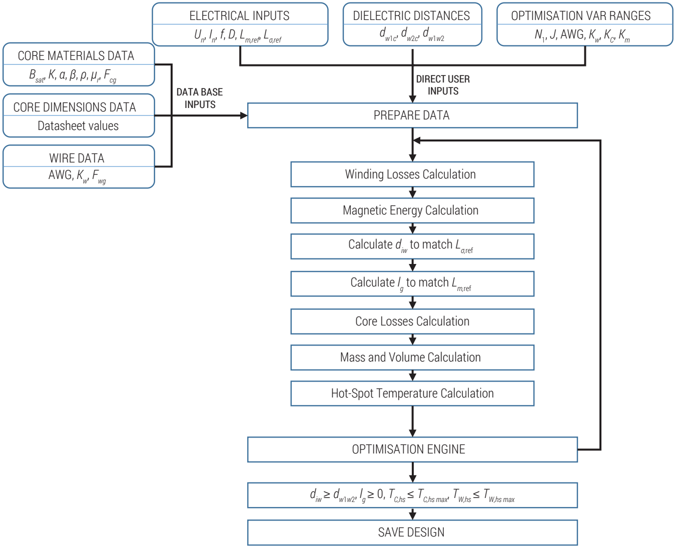
EPFL: 300kW, 2kHz



ETHZ: 166kW, 20kHz

CHALMERS: 50kW, 5kHz

DESIGN OPTIMIZATION: ALGORITHM



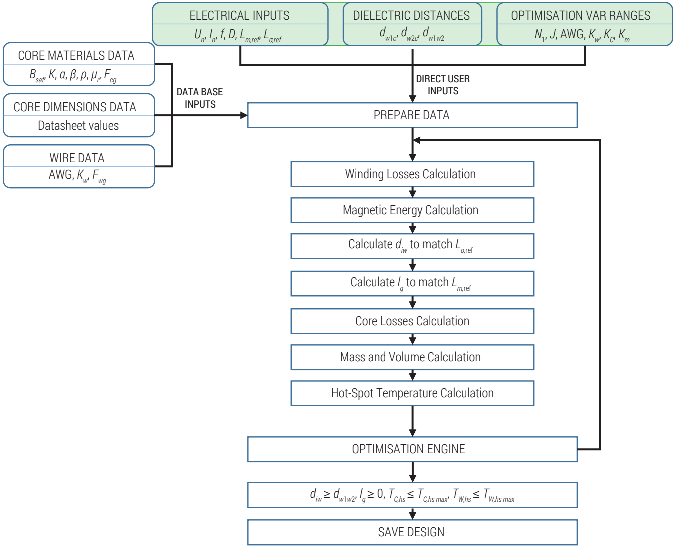
▲ MFT design optimization algorithm

Algorithm Specifications:

- Used Software Platform:
  - MathWorks MATLAB
- Used Hardware Platform:
  - Laptop PC (i7-2.1GHz, 8GB RAM)
- Performance Measure:
  - 59000 designs are generated in less than 190 seconds
- Electrical Specifications:

P_n	$100kW$	f_{sw}	$10kHz$
V_1	$750V$	V_2	$750V$
$L_{\sigma 1,2}$	$3.27\mu H$	L_m	$1.8mH$

DESIGN OPTIMIZATION: ALGORITHM



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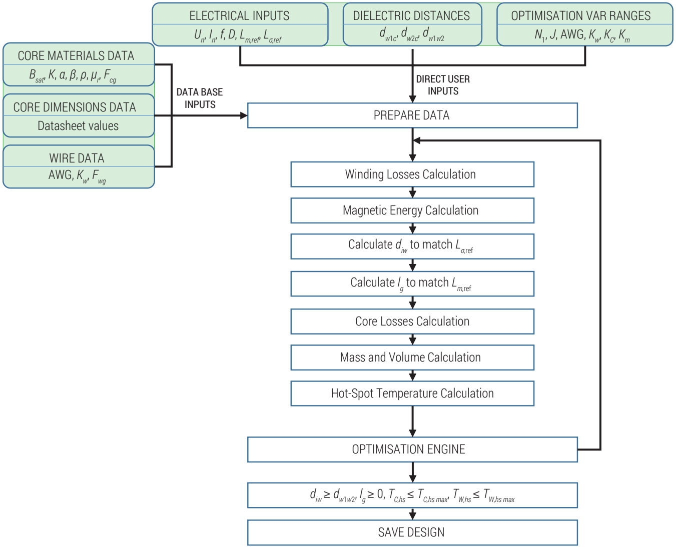
$L_{\sigma1,2}$	$3.27\mu H$	L_m	$1.8mH$

DESIGN OPTIMIZATION: ALGORITHM



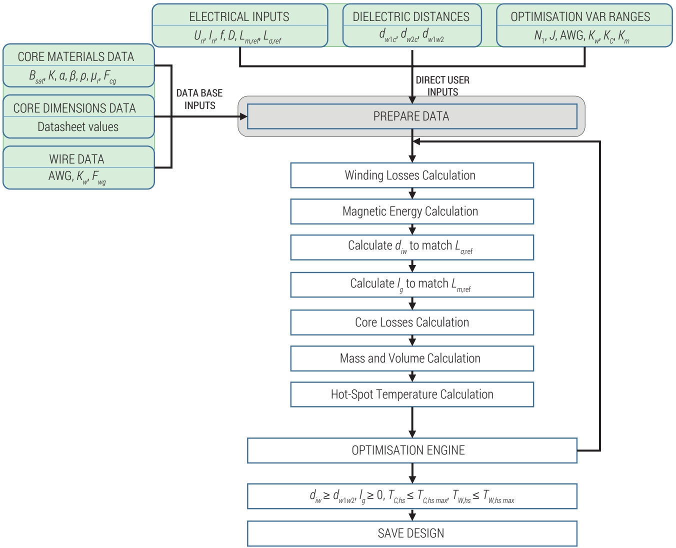
▲ MFT design optimization algorithm

Algorithm Specifications:

- Used Software Platform:
  - MathWorks MATLAB
- Used Hardware Platform:
  - Laptop PC (i7-2.1GHz, 8GB RAM)
- Performance Measure:
  - 59000 designs are generated in less than 190 seconds
- Electrical Specifications:

P_n	$100kW$	f_{sw}	$10kHz$
V_1	$750V$	V_2	$750V$
$L_{\sigma1,2}$	$3.27\mu H$	L_m	$1.8mH$

DESIGN OPTIMIZATION: ALGORITHM



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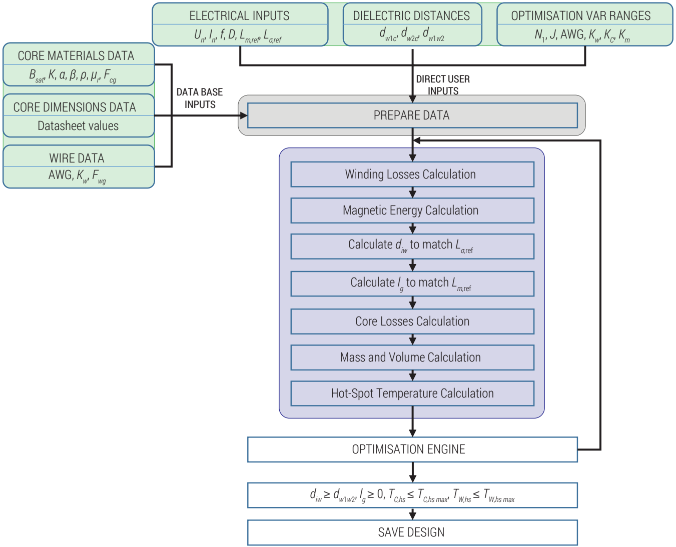
DESIGN OPTIMIZATION: ALGORITHM



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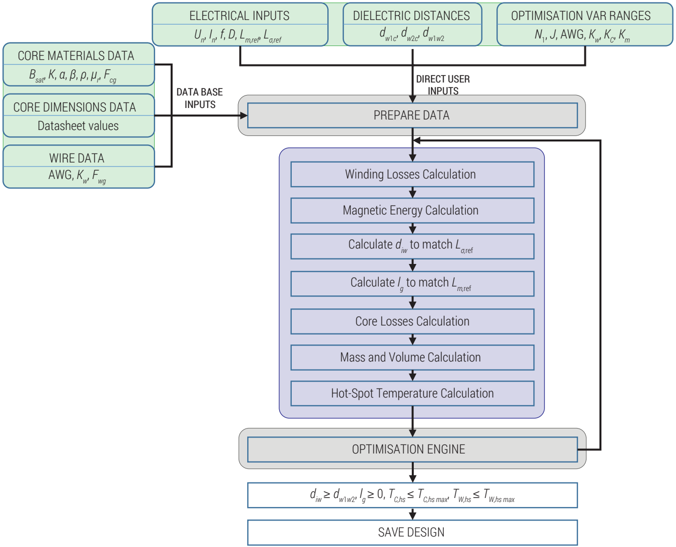
DESIGN OPTIMIZATION: ALGORITHM



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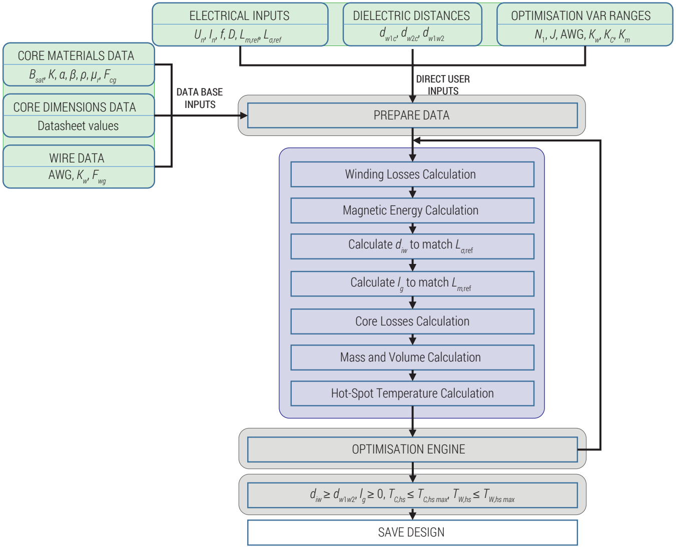
DESIGN OPTIMIZATION: ALGORITHM



▲ MFT design optimization algorithm

Algorithm Specifications:

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V_1	$750V$	V_2	$750V$
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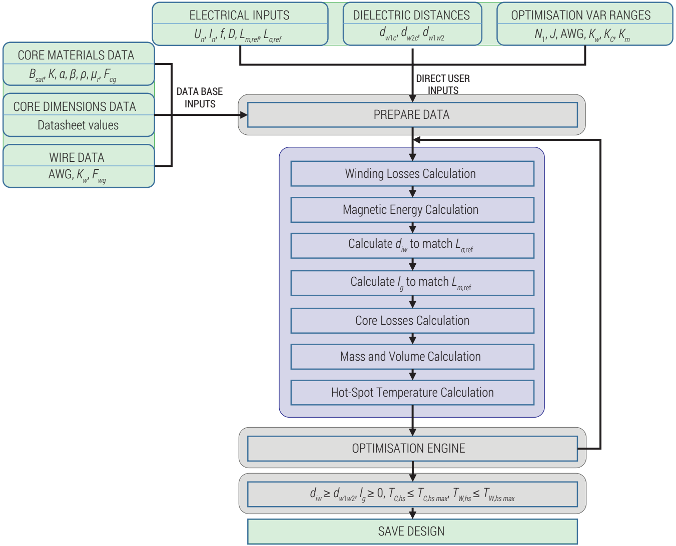
DESIGN OPTIMIZATION: ALGORITHM



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V_1	$750V$	V_2	$750V$
$L_{\sigma 1,2}$	$3.27\mu H$	L_m	$1.8mH$

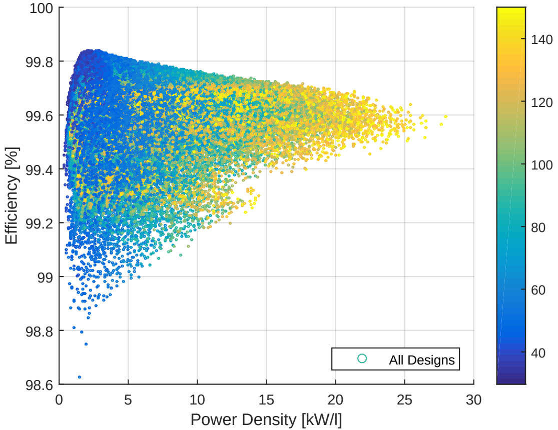
DESIGN OPTIMIZATION: RESULTS

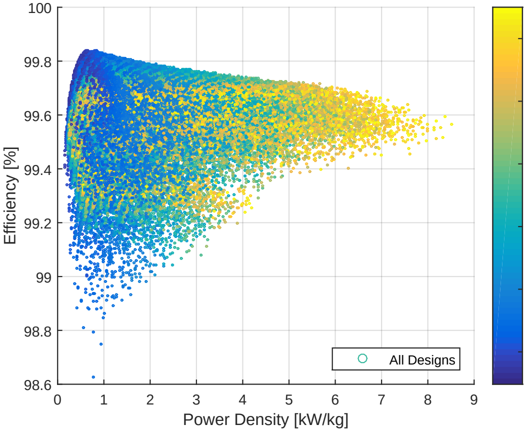
Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
150	100	/	/	/

Number of Designs:

- More than 1.8 Million





▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

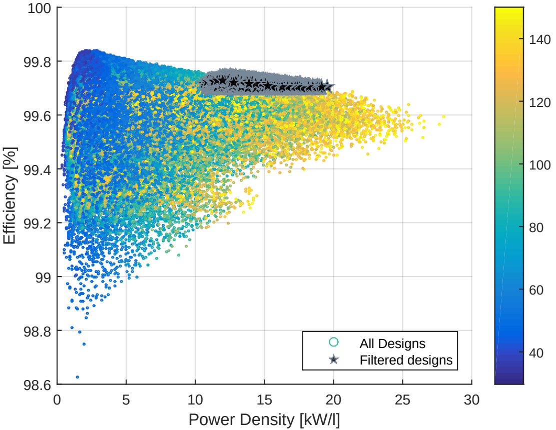
DESIGN OPTIMIZATION: RESULTS

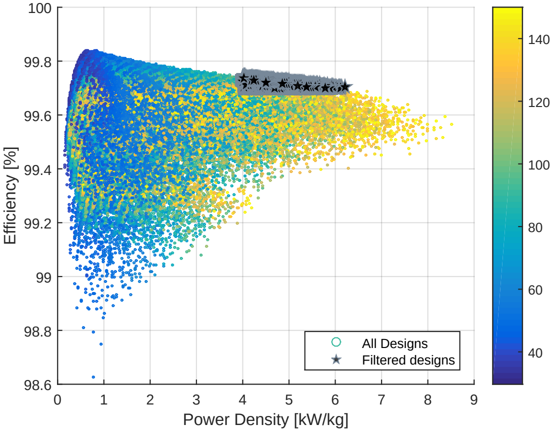
Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
150	100	12	25	99.7

Number of Designs:

- More than 1.8 Million





▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

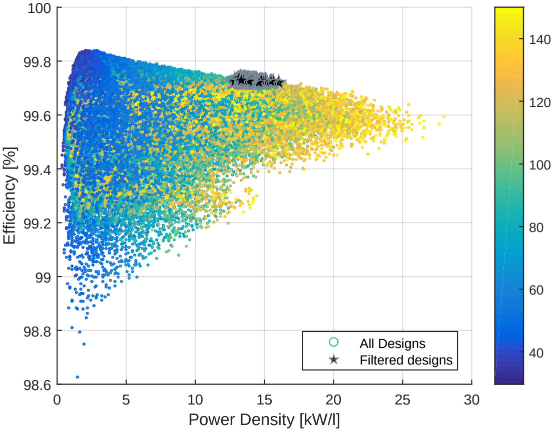
DESIGN OPTIMIZATION: RESULTS

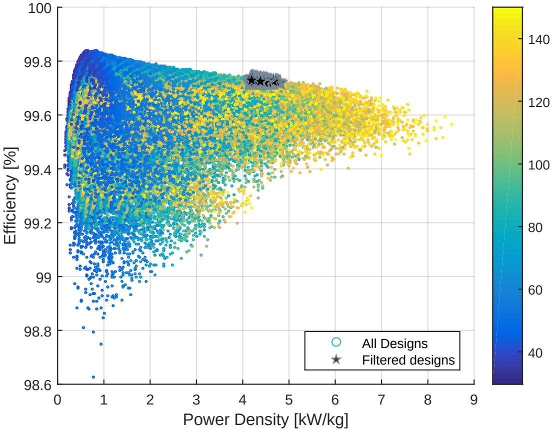
Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
130	80	9	24	99.72

Number of Designs:

- More than 1.8 Million





▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

DESIGN OPTIMIZATION: RESULTS

Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
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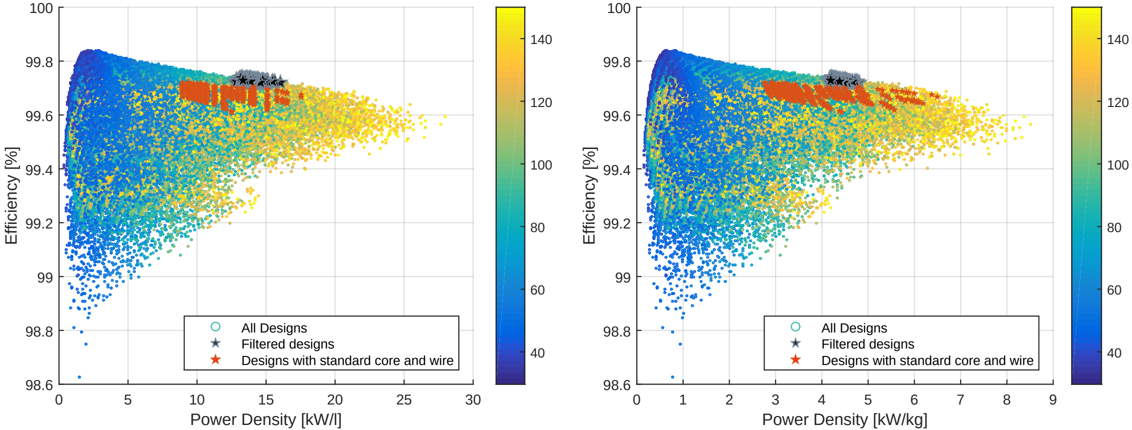


▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

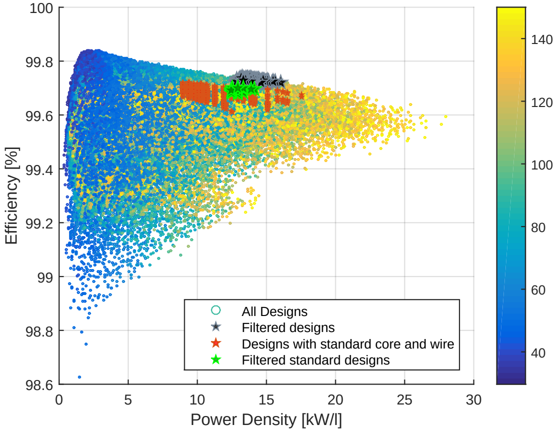
DESIGN OPTIMIZATION: RESULTS

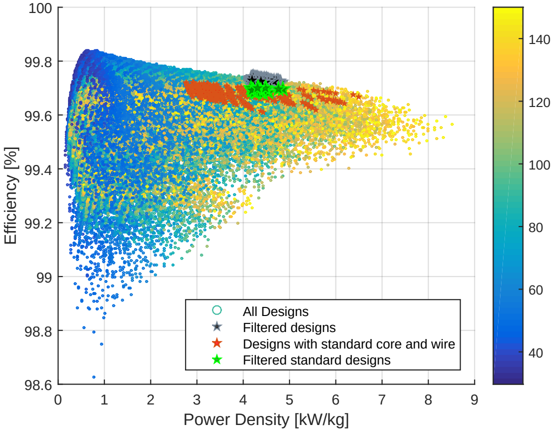
Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
135	80	10	24	99.6

Number of Designs:

- More than 1.8 Million





▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

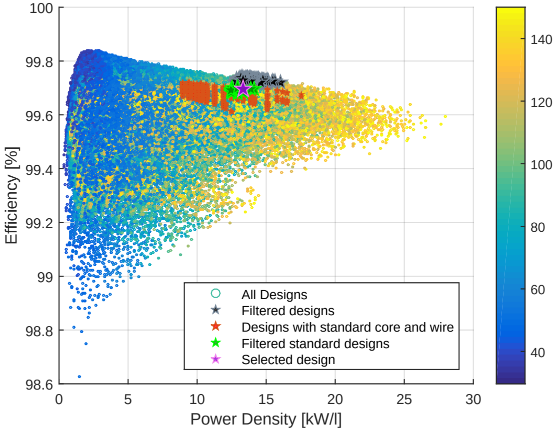
DESIGN OPTIMIZATION: RESULTS

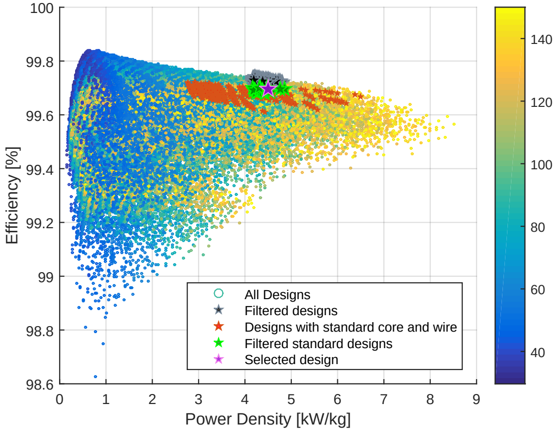
Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
135	80	10	24	99.6

Number of Designs:

- More than 1.8 Million



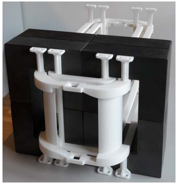


▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

PROTOTYPE: OPTIMAL MFT DESIGN ASSEMBLY


Optimal MFT Design 3D-CAD

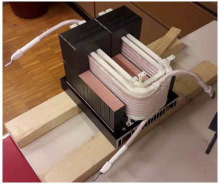

Coil-Formers 3D-CAD

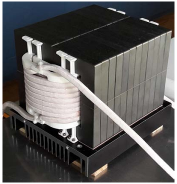

Coil-Formers 3D-Print


Primary Winding


Secondary Winding


Core Assembly


MFT Assembly1

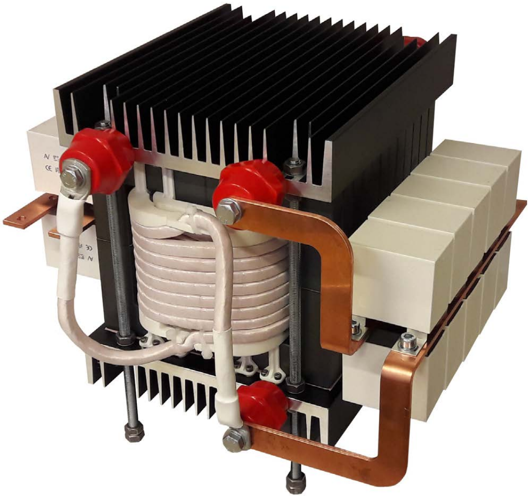

MFT Assembly2


Litz-Wire Termination


MFT Prototype

PROTOTYPE: FINAL ASSEMBLY

MFT Prototype



▲ 100kW, 10kHz MFT including resonant capacitors

Prototype Specifications:

- Core:
  - 12 stacks of 4 x SiFERRITE U-Cores (UU9316 - CF139)
- Windings:
  - 8-Turns
  - Square Litz Wire (8.7x8.7mm, 1400 strands, AWG 32, 43.69mm^2)
- Coil-Formers:
  - Additive manufacturing process (3-D printing)
  - High strength thermally resistant plastic (PA2200)
- Resonant Capacitor Banks:
  - (7x5μF + 1x2.5μF) AC film capacitors in parallel
  - Custom designed copper bus-bars
- Electrical Ratings:

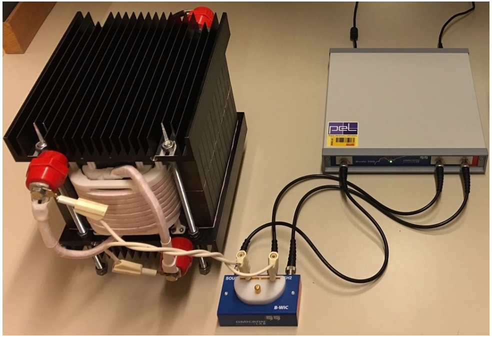
P_n	$100kW$	V_1	$750V$	$L_{\sigma 1,2}$	$4.2\mu H$
f_{sw}	$10kHz$	V_2	$750V$	L_m	$750\mu H$

MEASUREMENTS: ELECTRIC PARAMETERS

Measurement of Electric Parameters:

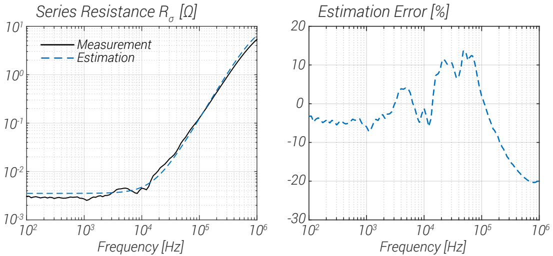
- Network Analyzer Bode100
- Impedance Measurement
- Results at 10kHz: $L_\sigma = 8.4\mu H$, $L_m = 750\mu H$, $R_\sigma = 0.2\mu\Omega$

LV Measurement Setup:

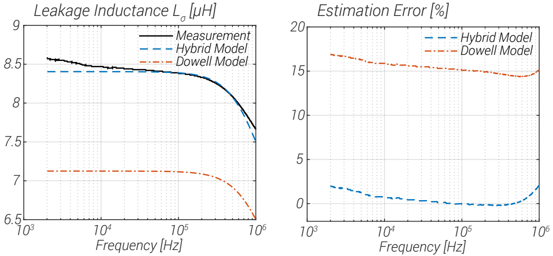


▲ Electrical measurements using Bode100

Series Resistance Measurement:



Leakage Inductance Measurement:

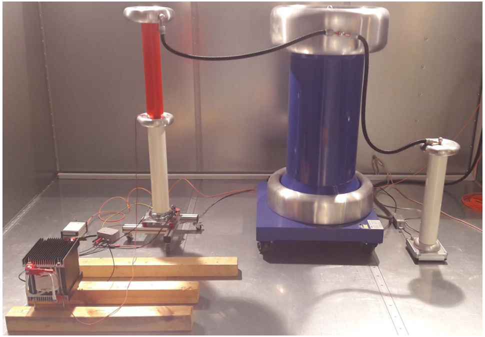


MEASUREMENTS: DIELECTRIC PARAMETERS

Dielectric Withstand Test:

- Partial Discharge measurement between all conductive parts
- High Voltage 50Hz source within a Faraday cage
- 10pC - between primary and secondary winding at 4kV

HV Measurement Setup:

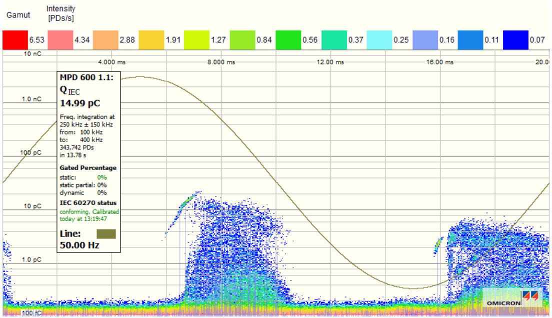


▲ MFT during AC test

PD Test Settings:

- Front of the voltage profile: $V = 6kV$
- Flat back of the voltage profile: $V = 4kV$
- Peak PD at periods where $|dV/dt|$ increases after the V peak
- PD is influenced by combination of V and $|dV/dt|$

Measured PD at flat back $V = 4kV$:

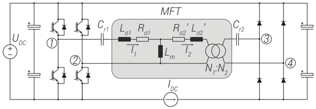


▲ MPD600 obtained measurement results

MEASUREMENTS: LOAD TEST

Test Setup Topology:

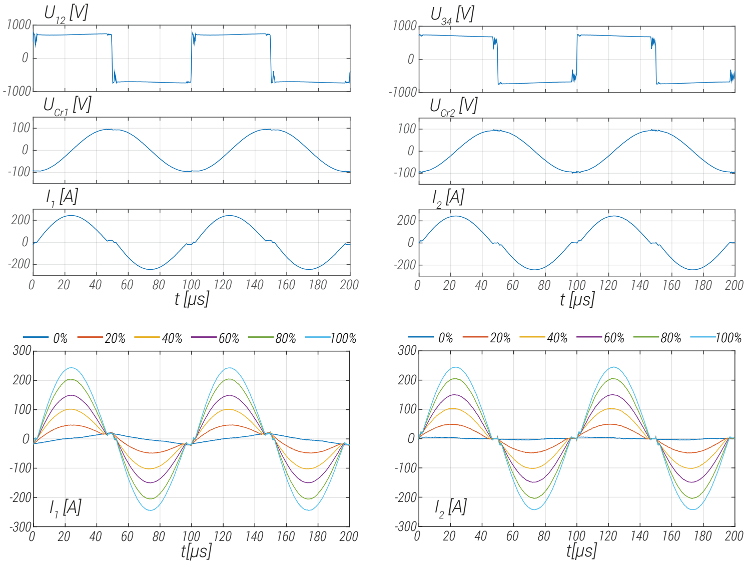
- B2B Resonant Converter
- Input voltage maintained by U_{DC}
- Power circulation via I_{DC}



Test Setup:

▲ B2B MFT test setup

Measurement Results:



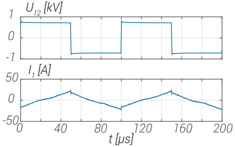
▲ Experimental results: left: MFT primary waveforms; right: MFT secondary waveforms

MEASUREMENTS: THERMAL RUN

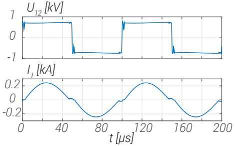
Measurement Setup:

Thermal Run:

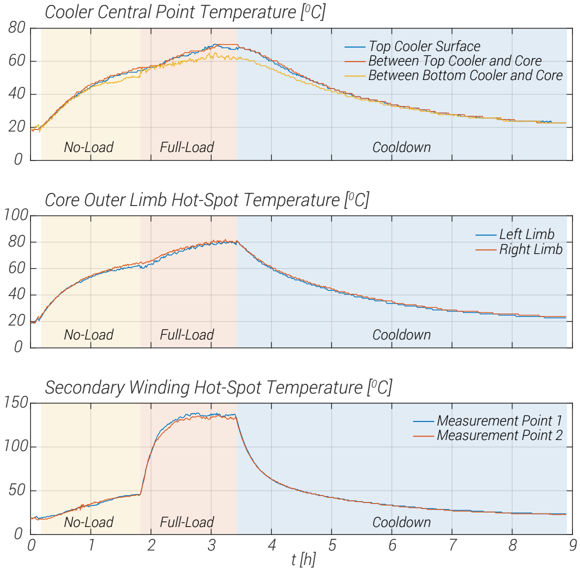
- No-Load Operation:



- Full-Load Operation:



Thermal Profile:



▲ Thermal heat run results

SENSITIVITY ANALYSIS

Case study considering DC-DC SST?

CONVERTER DESIGN: SELECTION OF NUMBER OF CELLS

Case Study ISOP Converter Specifications:

P_{tot}	500kW	V_{MVDC}	10kV	V_{LVDC}	750V

DC-DC Converter Cell Specifications:

$$V_{in} = \frac{V_{MVDC}}{N} \qquad V_{out} = V_{LVDC}$$

$$I_{in} = \frac{I_{MVDC}}{M} \qquad I_{out} = \frac{I_{LVDC}}{NM}$$

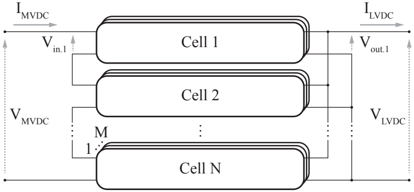
$$P_n = \frac{P_{tot}}{NM}$$

$$V_b > \frac{V_{MVDC}}{uN} \qquad I_{max} > \frac{I_{LVDC}}{NM}$$

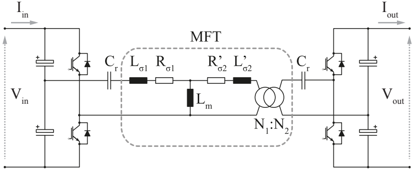
Semiconductor Blocking Voltage and N modularity:

V_b [kV]	N	V_{in} [kV]	u [p.u.]	f_{sw} [kHz]
1.7	11	0.91	0.53	25 (50)
3.3	6	1.67	0.51	10
4.5	4	2.5	0.56	5
6.5	3	3.33	0.51	1
10	2	5	0.5	/
20	1	10	0.5	/

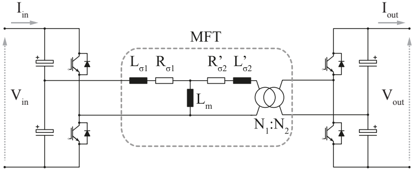
Modular ISOP Connection of DC-DC Converter Cells



SRC based DC-DC Converter Cell



DAB based DC-DC Converter Cell



CONVERTER DESIGN: DC-DC SRC CELL DESIGN

Case Study ISOP Converter Specifications:

P_{tot}	500kW	V_{MVDC}	10kV	V_{LVDC}	750V

DC-DC Converter Cell Specifications:

$$V_{in} = \frac{V_{MVDC}}{N} \qquad V_{out} = V_{LVDC}$$

$$I_{in} = \frac{I_{MVDC}}{M} \qquad I_{out} = \frac{I_{LVDC}}{NM}$$

$$P_n = \frac{P_{tot}}{NM}$$

$$V_b > \frac{V_{MVDC}}{uN} \qquad I_{max} > \frac{I_{LVDC}}{NM}$$

Semiconductor Blocking Voltage and N modularity:

V_b [kV]	N	V_{in} [kV]	u [p.u.]	f_{sw} [kHz]
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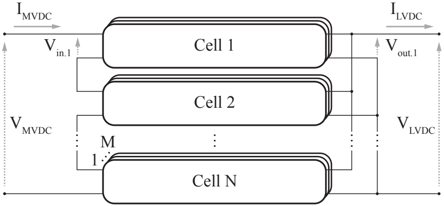
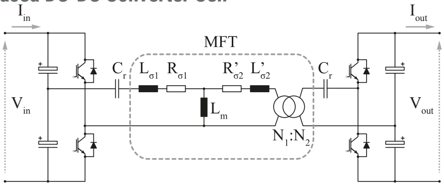
4.5	4	2.5	0.56	5
6.5	3	3.33	0.51	1
10	2	5	0.5	/
20	1	10	0.5	/

Modular ISOP Connection of DC-DC Converter Cells



SRC based DC-DC Converter Cell



Reference Resonant Tank Inductances ($f_o = 1.2 f_{sw}$):

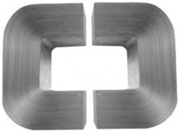
C_r	L_r	L_m
$\frac{\pi}{4.8Q} \frac{NP_{tot}}{Mf_{sw}V_{MVDC}^2}$	$\frac{Q}{1.2\pi^3} \frac{MV_{MVDC}^2}{Nf_{sw}P_{tot}}$	$\frac{1}{8I_{off}} \frac{V_{MVDC}}{Nf_{sw}}$

MFT DESIGN: SCOPE OF ANALYSIS

Core Materials:

- Ferrite
- Nanocrystalline

▲ Ferrite core - Isotropic



▲ Metglas core - Anisotropic

Considered Core Material Characteristics

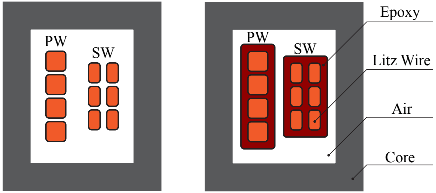
Core Material	B_{sat} [T]	K [kW/m^3]	α	β	ρ [kg/m^3]	λ [W/mK]
Si-Ferrite N87	0.39	$1.6 \cdot 10^{-3}$	1.42	2.16	4850	4
Nanocr-ystalline	1.17	$3.6 \cdot 10^{-5}$	1.64	2.10	7330	1.5 (8)

Considered Insulation Concepts:

- Air - Litz wire windings in the air
- Solid - litz wire winding cast in epoxy resin in the air
- Approximation of dielectric distances

$$d_i \approx k_s k_{pd} \frac{V_i}{V_b}$$

Considered Insulation Concepts



Considered Dielectric Material Characteristics

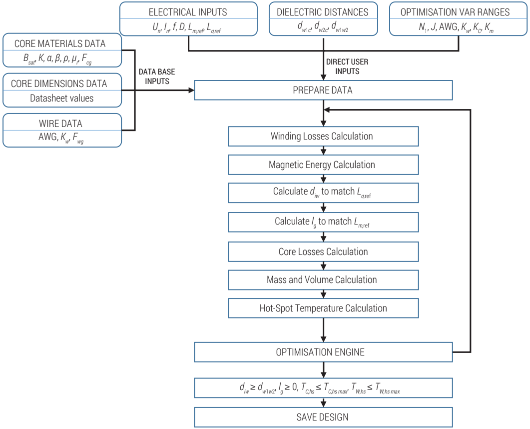
Material	V_d [kV/mm]	k_s	ρ[kg/m^3]	λ[W/mK]
Air	3	4	0	/
Epoxy	45	3	500	0.25

MFT DESIGN: METHOD OF ANALYSIS

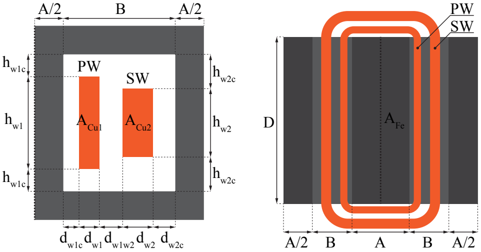
Generation of all possible MFT designs:

- For all practical M and N modularity variations
- For a range of frequencies f_{sw}: [0.5 – 50] kHz

MFT Design Optimization Algorithm



Generalized Geometry Definition



Parametric Optimization Variable Ranges

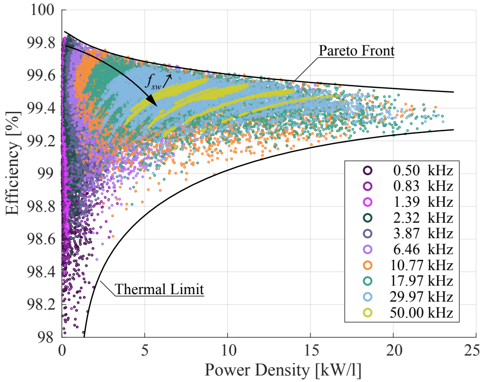
PW number of turns	N_1	1 – 50	/
Current Densities	$J_{mi} = \frac{I_n}{A_{Cui}}$	0.5 – 6	$\frac{A}{mm^2}$
Magnetic Induction	$K_m = \frac{B_m}{B_{sat}}$	0.2 – 0.9	p.u.
Win. Geom. Ratios	$K_{wi} = \frac{d_{wi}}{h_{wi}}$	0.05 – 0.5	p.u.
Core Geom. Ratios	$K_c = \frac{A}{D}$	0.05 – 0.5	p.u.

DESIGN ANALYSIS: FREQUENCY

Maximum feasible Si-Ferrite, Solid insulated MFT design set for $N = 11$, $M = 1$:

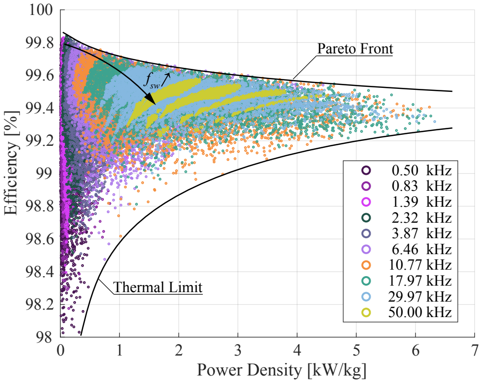
- Efficiency vs. power density Pareto front
- Thermal Feasibility Limit
- Feasible design set displacement in function of f_{sw}
- Approximately 12'000'000 designs in total
- Uniformly down-sampled to 66'000 designs for plotting
- Less feasible designs at higher frequencies (L_σ constraint)

Efficiency vs. volumetric power density



▲ Example for: Si-Ferrite, Solid Insulated, $N = 11$, $M = 1$

Efficiency vs. gravimetric power density

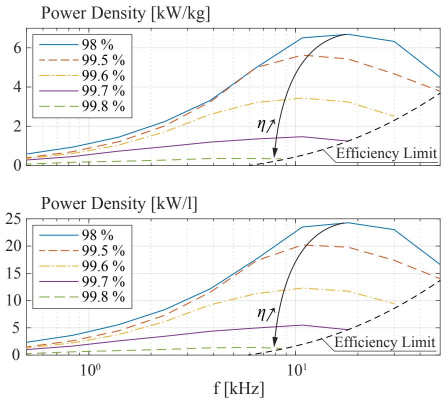


▲ Example for: Si-Ferrite, Solid Insulated, $N = 11$, $M = 1$

DESIGN ANALYSIS: FREQUENCY, EFFICIENCY AND INSULATION

Efficiency and Power Density:

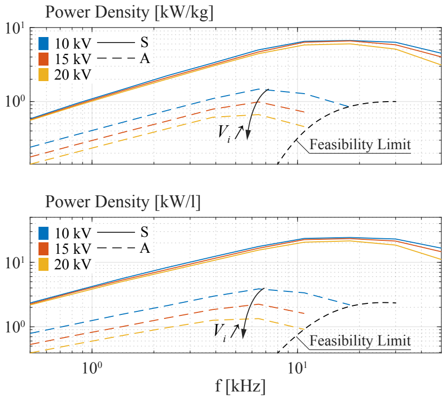
- Frequency scaling is not maintained at higher frequencies
- Max pow. dens. reaches the apex at some Pareto-optimal f_{sw}
- Max pow. dens. decreases as the η_{min} constraint is tightened
- Designs with higher η_{min} are infeasible at high f_{sw}



▲ Example for: Si-Ferrite, Solid Insulated, $N = 11$, $M = 1$

Insulation and Power Density:

- Max pow. dens. is lower for higher insulation voltage (V_i)
- Higher insul. voltage requires larger dielectric distances
- Air insul. yields inferior max pow. dens. compared to solid
- Air insul. design is much more sensitive to V_i increase

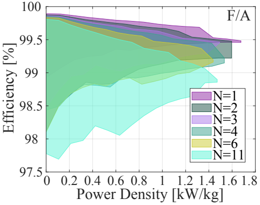


▲ Example for: Si-Ferrite, Solid Insulated, $N = 11$, $M = 1$

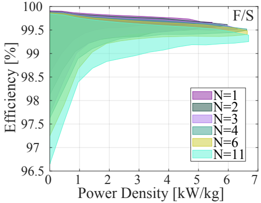
DESIGN ANALYSIS: N - MODULARITY

Gravimetric Power Density

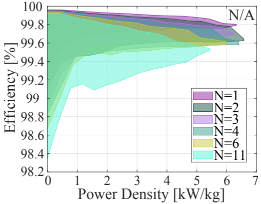
▶ Ferrite | Air



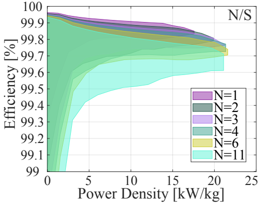
▶ Ferrite | Solid



▶ Nanocrystalline | Air

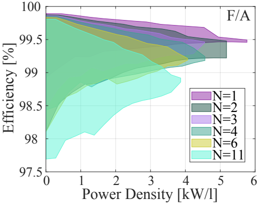


▶ Nanocrystalline | Solid

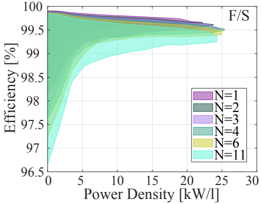


Volumetric Power Density

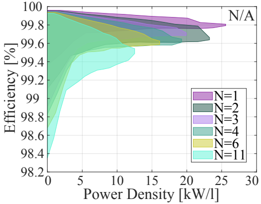
▶ Ferrite | Air



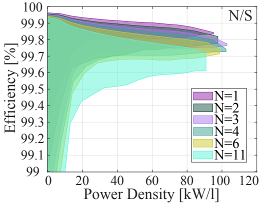
▶ Ferrite | Solid



▶ Nanocrystalline | Air



▶ Nanocrystalline | Solid



▲ Each surface represents an envelope around approx 12 Million designs

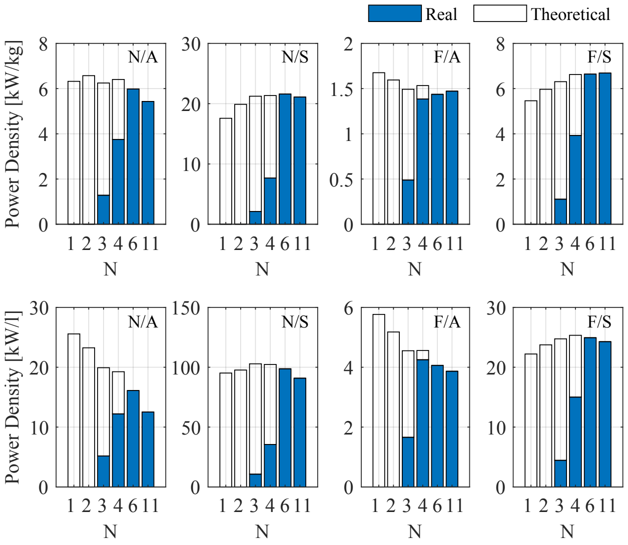
DESIGN ANALYSIS: N - MODULARITY AND SELECTED SEMICONDUCTOR INFLUENCE

Efficiency and Power Density:

- Highlights the difference between the real (existing Si semiconductors) and theoretical (emerging SiC) solutions
- High difference for realizations with low N due to low f_{sw} limit of high blocking voltage rated semiconductors
- The suboptimality gap decreases with the increase of N, where higher f_{sw} range is available
- N has a high influence on theoretical maximum volumetric power densities of Air insulated designs
- Total potential MFT max. pow. dens. increase (Theoretical-Si referred to Real-SiC)

Pow. Dens.	N/A	N/S	F/A	F/S
$\frac{kW}{kg}$ [%]	10	0	17	0
$\frac{kW}{l}$ [%]	62	3	50	2

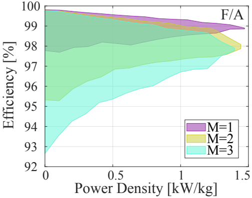
Maximum MFT Power Density: Real (Available Si) vs. Theoretical (Emerging SiC)



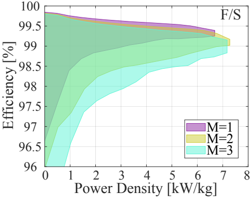
DESIGN ANALYSIS: M - MODULARITY

Gravimetric Power Density

- Ferrite | Air

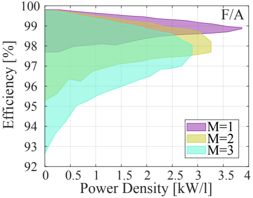


- Ferrite | Solid

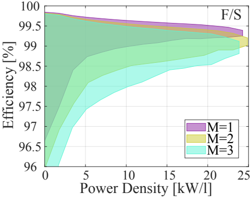


Volumetric Power Density

- Ferrite | Air

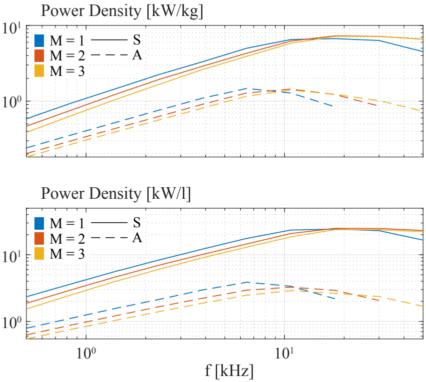


- Ferrite | Solid



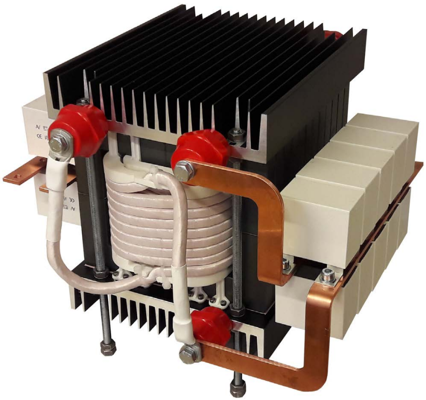
Increase of M modularity yields:

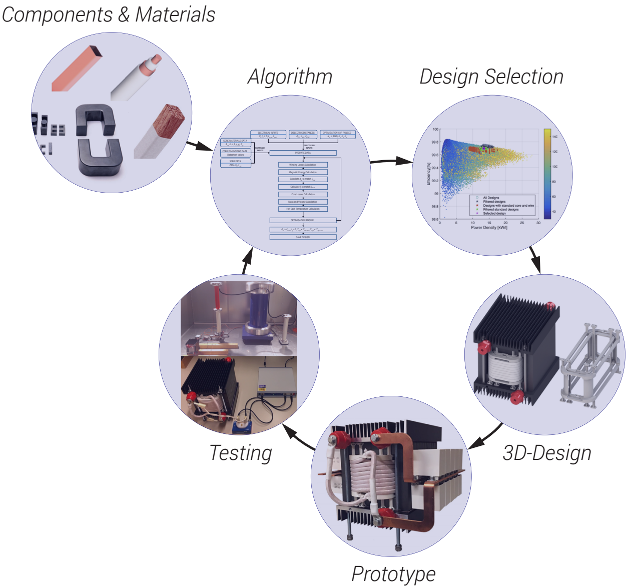
- Less efficient MFT design - tighter Pareto front
- Better relative cooling - relaxed thermal limit
- Designs with lower power density at lower f_{sw}
- Designs with higher Pareto optimal f_{sw}
- Designs with higher power density at high f_{sw}



CONCLUSION

- Complex and challenging design optimization
- Large number of available materials
- Customized designs prevail
- Research opportunities...





CONCLUSION

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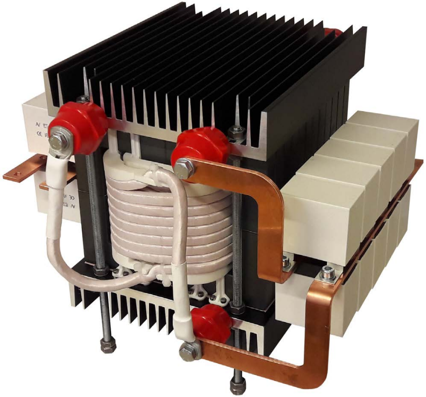

BIOGRAPHIES

Drazen Dujic is an Assistant Professor and Head of the Power Electronics Laboratory at EPFL. He received the Dipl.Ing. and MSc degrees from the University of Novi Sad, Novi Sad, Serbia in 2002 and 2005, respectively, and the PhD degree from Liverpool John Moores University, Liverpool, UK in 2008. From 2003 to 2006, he was a Research Assistant with the Faculty of Technical Sciences at University of Novi Sad. From 2006 to 2009, he was a Research Associate with Liverpool John Moores University. After that he moved to industry and joined ABB Switzerland Ltd, where from 2009 to 2013, he was Scientist and then Principal Scientist with ABB Corporate Research Center in Baden-Dättwil, and from 2013 to 2014 he was R&D Platform Manager with ABB Medium Voltage Drives in Turgi. He is with EPFL since 2014.

His research interests include the areas of design and control of advanced high power electronic systems and high-performance drives, predominantly for the medium voltage applications related to electrical energy generation, conversion and storage. He has authored or co-authored more than 100 scientific publications and has filed twelve patents.

In 2018 he received EPE Outstanding Service Award from European Power Electronics and Drives Association (EPE) and 2014 The Isao Takahashi Power Electronics Award for Outstanding Achievement in Power Electronics. He is Senior Member of IEEE, EPE Member, and serves as Associate Editor for IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics and IET Electric Power Applications.

Marko Mogorovic received the Dipl.Ing. degree from the University of Belgrade, Belgrade, Serbia, in 2013 and MSc degree from the École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland, in 2015. Currently, he is pursuing the Ph.D. degree at Power Electronics Laboratory at EPFL, Lausanne, Switzerland. His current research focus is on the design optimization of the high power medium frequency transformers for medium voltage applications and emerging solid state transformers.

He is an IEEE Student Member and EPE Student Member.

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TERMS AND DEFINITIONS (I)

Coercive field strength – H_c

- Magnetic field strength required to demagnetize a material

Curie temperature – T_c

- The temperature where the material becomes paramagnetic and losses its permeability
- Reversible

Cut-off frequency

- Permeability shows a pronounced drop above a certain frequency

Disaccommodation

- Fractional decrease of the permeability with time under constant operating conditions
- Special case of magnetic relaxation

Eddy currents & losses

- Induced currents in the magnetic material from a changing magnetic field
- Increase with flux density
- Decrease with higher electrical resistivity

Flux density, magnetic induction

- Induced currents in the magnetic material from a changing magnetic field
- The magnetic flux per unit area perpendicular to the direction of the magnetic force

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

TERMS AND DEFINITIONS (II)

Frequency dependence (response)

- Increasing frequency widens the hysteresis loop
- Mainly caused by eddy currents

Hysteresis loops

- Relationship between the magnetic field strength and flux density for complete magnetization cycle
- Three basic shapes – round (R), square (Z) and flat (F)

Hysteresis – losses

- Portion of losses caused by hysteresis
- Proportional to the area enclosed by the loop
- Increases with frequency

Magnetic constant - μ_0

- Universal constant in free space

$$\mu_0 = 4\pi \cdot 10^{-7}$$

Inductance

- Electrical quantity derived from permeance

$$L = N^2 \cdot A_L = N^2 \cdot \frac{A_e}{l_e} \cdot \mu_0 \cdot \mu$$

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

TERMS AND DEFINITIONS (III)

Loss angle δ

- Phase shift between the magnetic flux density and the magnetic field strength
- Derived from real and imaginary part of complex permeability
- Ratio of ohmic resistance of coil or core and its reactance
- Measure of the magnetic power loss

Magnetic field strength - H

- Calculated from Ampere's Law
- The line integral of the magnetic field strength over a closed path
- Also referred to as magnetomotive force (mmf)

Magnetic materials

- Classified as 'hard' or 'soft' according to coercivity (H_c)
- Soft: $H_c < 10^3 A/m$
- Hard: $H_c > 10^3 A/m$

Magnetostriction

- Deformation in shape of material with magnetization

Penetration depth, Skin depth

- The depth at which the field strength falls to 1/e (about 37%) of surface value

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

TERMS AND DEFINITIONS (IV)

Absolute Permeability, μ_0

- The ratio of flux density (B) to magnetic field strength (H)
- In free space equals the magnetic constant μ_0

Amplitude Permeability, μ_a

- Relative permeability with ac magnetization
- Slope of straight line from origin ($H = 0, B = 0$) to any point on initial magnetization curve

Complex Permeability, μ_p', μ_p''

- Because there is a phase shift between the flux density and magnetic field strength
- It is a complex quantity

Differential Permeability, μ_{dif}

- The relative permeability at a given point on the magnetization curve for very small variations

Effective Permeability, μ_e

- Used to describe magnetic circuits with non-homogenous cross sections or for cores consisting of different materials or those with air gaps

Incremental Permeability, μ_Δ

- The relative permeability for ac magnetization with a specific value of superimposed dc bias

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

TERMS AND DEFINITIONS (V)

Initial Permeability, μ_i

- The amplitude permeability for a very small flux density

Maximum Permeability, μ_{max}

- The maximum value of the amplitude permeability

Pulse Permeability, μ_p

- The ratio of flux density swing ΔB to corresponding field strength excursion ΔH

Relative Permeability, μ_r

- The ratio of the absolute permeability to the magnetic constant
- This is usually seen without the subscript and the value used in core catalogs

Remanent Permeability, μ_{rem}

- Relative permeability for small ac excitation after previously applied field is reduce to zero

Reversible Permeability, μ_r

- Relative permeability for small ac excitation a superimposed dc field

RMS amplitude Permeability, p

- The ratio of peak flux density to the rms value of the magnetic filed strength

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

TERMS AND DEFINITIONS (VI)

Permeance, A_L

- Also known as inductance factor
- Inductance of one turn on a specific core

Power losses (core losses)

- The energy lost to magnetization of the material
- Includes both hysteresis losses and eddy current losses

Quality factor

- Reciprocal of the loss angle tan δ

Reluctance, R_m

- Magnetic resistance – reciprocal of permeance

Remanence, B_r

- The flux density remaining after a previously applied field is reduce to zero

Saturation

- The point where all the atomic magnetics are aligned parallel to the magnetic field

Shearing the hysteresis loop

- Flattening of the hysteresis loop from an air gap in the magnetic path

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar

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Q AND A

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HIGH POWER MFT DESIGN OPTIMIZATION

Drazen Dujic & Marko Mogorovic
École Polytechnique Fédérale de Lausanne
Power Electronics Laboratory
Switzerland

EPFL